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MESTRADO EM DESIGN INDUSTRIAL E DE PRODUTO

Going Mars, the beginning of a printed living machine

Development of 3D printed structures with *in-situ* resources

Filipa Freitas Soares

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Going Mars, the beginning of a printed living machine

Development of 3D printed structures with *in-situ* resources

Filipa Freitas Soares

Dissertation for Master's Degree in Product and Industrial Design

Dissertation advised by

Doctor Carlos Casimiro Costa

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Resumo

A perspetiva de aventura que leva a espécie humana a procurar novas fronteiras para explorar, talvez esteja gravada no nosso ADN. A descoberta de novos mundos, novas oportunidades e novas formas de ver a Terra e o Sol são algumas das razões pelas quais exploramos o espaço. Para além disso, a possibilidade de a humanidade poder estar ameaçada devido a desastres naturais ou provocados pelo homem, leva-nos ao pensamento de colonizar o espaço, começando pelos planetas mais próximos e eventualmente outros sistemas solares.

Marte é o planeta mais próximo e mais habitável do sistema solar, depois da Terra, e já tem sido alvo de exploração robótica. Os primeiros humanos a pisar Marte terão tudo em comum com os exploradores que escalaram montanhas e navegaram oceanos no passado. A diferença é que, antes, eles exploravam um meio desconhecido tangível, pois sabiam que iam encontrar água, terra, plantas, animais, seres humanos e provavelmente outras culturas. Desta vez, os aventureiros vão partir para o desconhecido intangível, pois aparentemente o planeta Vermelho não tem "nada" para oferecer para além de rochas, poeira e um *pôr-do-sol vermelho*. Os humanos terão de construir num território vazio e criar uma nova paisagem doméstica artificial.

Este projeto propõe o design de uma habitação marciana destinada a ser construída dentro dos tubos de lava encontrados ao longo de todo o planeta. Os tubos protegem os humanos contra o ambiente hostil da superfície de Marte e o uso de recursos *in-situ*, nomeadamente o basalto, diminuirá os custos de envio de materiais a partir da Terra. Inspirado pela natureza, o design do habitat segue uma abordagem modular, adaptando-se a qualquer espaço e crescendo continuamente. O uso da tecnologia de impressão 3D nas estruturas da habitação simplifica o processo de fabrico. A análise dos rituais envolvidos na vida doméstica e objetos do cotidiano irá direcionar o design de um habitat centrado no utilizador, que promova o conforto e o bem-estar neste novo paradigma de vida e interação entre homem e máquina.

Palavras-chave: Exploração de Marte, Habitação marciana, Paisagem doméstica, Design, Basalto, Impressão 3D

Abstract

The prospect of adventure that compels the human species to seek new frontiers to explore is perhaps engraved in our DNA. Discovering new worlds, new chances and new ways of seeing Earth and the sun are some of the reasons why we explore space. Also, the possibility that mankind may be endangered due natural or man-made disasters, lead us towards the thinking of colonizing space, starting by the nearest planets and ultimately other solar systems.

Mars is the nearest most habitable planet in the solar system after Earth and has already been a target for robotic exploration. The first humans to set foot on Mars will have everything in common with the explorers who scaled mountains and sailed oceans in the past. The difference is that, before, they searched a tangible unknown medium since they knew they were going to find water, land, plants, animals, human beings and probably other cultures. This time, adventurers will departure to the complete unknown because apparently the Red planet has “nothing” to offer, except rocks, dust and a *red sunset*. Humans will have to build on an empty territory and create a new artificial domestic landscape.

This project proposes the design of a Martian dwelling intended to be built inside the lava tubes found across the whole planet. The tubes protect humans against the harsh environment of the surface of Mars and the use of *in-situ* resources, namely basalt, will diminish the costs of sending materials from Earth. Inspired by nature, the design of the habitat follows a modular approach, adapting to any space and growing continuously. The use of 3D printing technology in the structures of the settlement simplifies the manufacture process. Analysing the rituals involved in the domestic life and everyday objects will improve the design of a user-centred habitat that enhances comfort and well-being in this new paradigm of living and interaction between man and machine.

Keywords: Mars exploration, Martian dwelling, Domestic landscape, Design, Basalt, 3D printing

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The journey of this master's thesis was long but passionate and it would not have been the same without the help of a number of people who certainly made it more interesting, richer, fun and exciting.

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A special thanks to my parents, brother and sister for always being there and unconditionally supporting me, and my dear friends Tiago, Cláudia and Isa for their constant belief in me, patience, support and encouragement.

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Symbols, Acronyms and Terms

Symbols

˚C - Celsius Degree

% - Percentage

cm - Centimetre

CO_2 - Carbon Dioxide

GPa - Giga Pascal

kg - Kilogram

km - Kilometre

km^3 - Cubic kilometre

km/h - Kilometre per hour

km/s - Kilometre per second

m - Metre

m^2 - Squared metre

m/s^2 - Metre per second squared

m^3 - Cubic metre

mm - Millimetre

t/m^2 - Tone per Square Metre

Acronyms

3D - Three-dimensional

ABS - Acrylonitrile Butadiene Styrene

ADN - Ácido Desoxirribonucleico

ATHLETE - All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer

BFRP - Basalt Rebars

CNC - Computer Numerical Control

DNA - Deoxyribonucleic Acid

ESA - European Space Agency

FACS - Freeform Additive Construction System

FBAUP - Faculdade de Belas Artes da Universidade do Porto

FDM - Fused Deposition Modelling

FEUP - Faculdade de Engenharia da Universidade do Porto

GCR - Galactic Cosmic Rays

ISRO - Indian Space Research Organization

ISRU - *In-situ* Resource Utilization

LDPS - Laboratório de Desenvolvimento de Produto e Serviços

MDIP - Mestrado em Design Industrial e de Produto

NASA - National Aeronautics and Space Administration

PE - Polyethylene

PLA - Polylactic Acid

SPE - Solar Particle Events

TBM - Tunnel boring machines

USA - United States of America

USGS - United States Geological Survey

USSR - Union of Soviet Socialist Republics

WWWWWH - Who? What? Where? When? Why? and How?

Terms

Regolith - material derived from the layer of unconstrained rock material covering the Martian surface.

Terraform - transform a celestial body in order to resemble the Earth, especially to make it capable of supporting human life.

Figure 1 - "I want to go to Mars. Not just to visit. I want to live there". Images retrieved from the movie *The Space Between Us* (Chelsom 2017)

Figure 2 - "The Martians will be us" - Carl Sagan
in the 1980's TV Series *Cosmos* (Sagan and Druyan 1980).

The possibility that human race may be endangered on planet Earth, due to events such as natural or man-made disasters, global warming, depletion of natural resources, population growth, among others, lead us towards the need to think of ways to save the planet, as well as the search for other planets to inhabit in order to prevent man's extinction. Long before that happens, humankind must become a spacefaring species, capable of living not only on another planet but ultimately in other solar systems. However, more than the preservation of the human species, the most important reason for today's space exploration is the discovery of new worlds, new chances, new ways of seeing the sun, new ways of seeing Earth and a great opportunity for scientific exploration.

Perhaps the need to explore is engraved in our DNA; *homo sapiens* began their adventure out of Africa about 60,000 years ago, pushing beyond the horizon until they populated the entire globe. Today we must do the same by colonizing other planets, starting by the nearest ones - Mars. The first Martian explorers, alone on a seemingly lifeless planet as much as 225 million kilometres away from home, have everything in common with the explorers who scaled mountains and sailed oceans to find new worlds in the past. The difference is that in the past adventurers departure was into a tangible unknown medium because they knew they were going to find water, land, plants, animals, human beings and probably other cultures. This time, adventurers will departure to the complete unknown because apparently Mars has "nothing" to offer, except rocks, dust and a *red sunset*.

The only way to a viable colonization of other planets is by sending multicultural families and specialized volunteers. Just like before in the era of the great discoveries, humans will have to depart with a selection of seeds, plants, animals, gene banks, water, food, robots, 3D printers and new faith for a better world. They will have to build in an "empty" landscape, a new scenario and a new sense of dwelling where artificiality will be created, crafted, printed and redesigned.

Landing people on Mars will represent the greatest achievement of human intelligence. It will expand our vision beyond the bounds of Earth's gravity, since we will become a multi-planetary species (Petranek 2015). There is already a number of completed and ongoing projects regarding Mars exploration and possible colonization. Some of the most important ones are the *Mars One* project, the *Mars 500* project, the *Mars Direct* project, *Falcon Heavy* rocket from SpaceX, the NASA's *Journey to Mars* project, the *3D-Printed Habitat Challenge Design Competition* contest launched by NASA, and the *Mars Science City* project.

For the design process and proposal it will be necessary to understand the meaning of home, domestic life, everyday objects and their complexity, taking into account the relation of scale, territory and space of the new Martian landscape. The design of these elements in the dwelling scenario need to attend a new way of living and respond by adapting to the environment and to the interactions between machine, architect, engineer and designer. New materials will be at disposal, reinvention of basalt stone applications and the use of other resources from the territory. Also, new 3D printing technologies will allow the adjustment of the habitat to Martian lava tubes producing a new urban dynamic inside a cavernous space, evoking the Allegory of the cave by Plato and the beginnings of time where men lived inside caves. New understandings of the individual and communal space will arise. There will be a return to the primitive sense of the self, new utopias, returning to the beginning, to the cave, to the origins, to our own idea of man. Thus, the design culture will enter a new level. In that sense a new design that will materialize on new intentions.

"The human exploration of Mars is not a task for some future generation. It is a task for ours. We hold it in our power to begin the world anew. *Let's do it"* – Robert Zubrin
in the book *The Case for Mars* (Zubrin 2011).

Objectives and Goals

Assuming that all the barriers of the trip to Mars, the harsh environment and the psychological and social impact of prolonged isolation are overcome, the aim of this thesis is the presentation of a design proposal for a dwelling on Mars.

There is still a huge gap in the field of Martian architecture and extra-terrestrial design, so in order to narrow it the primary focus was on the design of structures that would enhance inhabitant's comfort and well-being. Also, the understanding on the rituals and ceremonies involved in the domestic landscape will be closely analysed as well as new concepts of homes and everyday objects, associating to these topics the circumstances and idiosyncrasies of "living and being".

In a first approach, through the literature review, it is proposed the reflection on society in general and the ideal society, to perceive the evolution of man and, in the context of contemporaneity and history, to try to distinguish the contexts of its development and their languages: modernism, postmodernism and the third way in the direction of a liquid modernity.

In a second and more empirical approach, the goal is to design a sustainable, self-sufficient and user-centred dwelling by:

- Minimizing launch mass and the necessity of supply cargo through the use of *in-situ* resources;
- Utilizing simplified manufacturing processes like 3D printing with sustainable *in-situ* resources to build the habitat and protect it against the environment of Mars;
- Providing flexible habitat designs to provide optimum living and working conditions for the settlers and space-saving adaptable structures to be deployed and expanded anywhere;
- Including private individual spaces and bigger spaces for families and communal activities
- Conceding the possibility of customization of the interior habitat to the settlers in order for them to feel comfortable and at peace.

Methodology

The development of this thesis was accompanied by a series of methodologies that cover the investigation process and the design process.

For the first part an extensive investigation was made on the contextualization of the subject, namely on the exploration and colonization of Mars, on the planet Mars itself and other things that involve space exploration. For this purpose several articles from scientific journals, conference papers, books, master and doctoral dissertations, as well as websites and scientific websites were utilized.

In addition to the planet Mars, the concept of housing and the rituals of domestic life were analysed and synthesized in order to understand the key points to be explored in this work. Design books were mainly used for this direction. The historical utopias and design utopias were also approached in the reading of articles, books, and design books.

A brief investigation was done in the field of 3D printing technology, mainly in scientific articles and websites, and a deeper investigation on basalt and basalt fibre was done by the contact of two European companies.

For the second part, the design process was guided by the Delft Design Guide (Boeijen and Daalhuizen 2010). A set of design methods such as *Collage Techniques*, *The ZEN Design Method*, *Trends Analysis*, *WWWWWH*, *Problem Definition*, *Checklist for Generating requirements*, *Design Specification (Criteria)* and *Process Tree, Brainstorming* and *Mind Map* were selected and followed. The definition of the Design Program was inspired by Emilio Ambasz's design program in *Italy: The New Domestic Landscape* (Ambasz 1972).

Three-dimensional modelling was developed in the *SolidWorks* software and for rendering the *Keyshot* software was used. The prototype was printed on a *Makerbot Replicator 2X* 3D printer with PLA.

Document's structure

The structure that organizes this thesis is divided in five main chapters.

The first chapter presents a general introduction to the theme and introduces the basic concepts for the development of all the work presented. Apart from that, it also presents the objectives and expected goals to be achieved, as well as the methodology used and the structure of the document.

The second chapter justifies the choice of the planet Mars as the destination of exploration and colonization in relation to other planets. It also presents the main differences between this planet and the planet Earth as well as further features on the Red planet.

Then, chapter 3 exposes the literature review and state of the art on the subject. This chapter is divided into two major sub-chapters. The first subchapter presents plans related to the exploration and colonization of Mars, which in turn is divided into three subchapters - plans designed for what precedes man's arrival on the planet, plans that are developed for the moment when the first man sets foot on Mars and, finally, plans for the expansion of the first settlements and dreams for a more distant future. The second subchapter includes other projects that are not directly related to Mars but which are relevant to the development of this thesis. It is in turn divided into five sub-chapters that include design projects, examples of structures, modular objects, 3D printing projects, and interesting materials.

Chapter four summarizes the whole design process that resulted in the printed prototypes and presents the design specifications, the design program for the development of the design proposal, the search for the form, the final design of the individual module and the colony, the suggested materials and manufacturing process and, in the end, presents other design possibilities.

Finally, the fifth chapter closes this thesis with the conclusions drawn from all the work developed and presents the limitations of the project and suggestions for future work. The appendix presented at the end of the document show, among others, more detailed information on the basalt textiles sent by the Vulkan-Europe B. V. and Swisstulle Ltd. companies.

Chapter 2 | Exploration and Colonization of Mars

Figure 3 - Spaceship for Mars exploration.
Image retrieved from the movie *The Martian* (Scott 2015).

"It is already known by images obtained from Hubble telescope and Earth based observatories that the universe has trillions of planets. This understanding triggers the idea that humans can inhabit them in the future, starting by the closest ones and then moving to farther planets."
(Sheshpari, Fujii, and Tani 2017)

The solution for a possible overpopulation of planet Earth can be the colonization of space. Regarding some authors, maybe we will start by building colonies in Earth's orbit and then move to farther places in space, but in this case it will probably be a trip without return. If scientific space stations and industrial applications search for microgravity, "residential" space stations will definitely have to own artificial gravity because humans are not able to live for a long time without the lack of gravity causing irreversible damage in their health. Imagined since Wernher von Braun (Petranek 2015), a wheel-shaped space station spinning on itself could compensate for the lack of gravity thanks to centrifugal force. Since these stations would be near the Earth, their inhabitants could frequently visit their home planet. On the other hand, distant colonies, would almost entirely be disconnected from Earth, except for the radio communications. Until today it is not possible, for a spaceship to reach more than a few hundred thousand km/h and it does not seem likely in the near future. This means that a return to Earth would take several tens of years if not more. The adventurers and volunteers for these distant colonies should depart in great numbers, and take off with a lot of spaceships that will be like the Arks of Noah, carrying selections of plants, animals and gene banks to prevent degeneration. The colonies of space will be in truth new worlds (Bon et al. 2000).

Why Mars?

The nearest place to Earth is our moon, but its near-vacuum environment, broad temperature range and long day/night rhythm, turns it into a hostile environment for human settlement. Venus is the closest planet to Earth, however it is also the hottest planet in the solar system, making it impossible for humans to live in. Mars, on the other hand, is not too hot nor too cold, and has an atmosphere to protect humans. Its day/night duration is very similar to Earth's (Wan, Wendner, and Cusatis 2016), with a duration of about 24 hours and 37 minutes (NASA 2018b). Therefore, Mars is the most habitable planet in the solar system after Earth (Wan, Wendner, and Cusatis 2016).

Mars has been enthusing humanity for some time (Kading and Straub 2015). From the middle of the 20th century until the end, many projects for manned missions to Mars have been proposed by the Soviet Union (USSR), the United States (NASA), Europe (ESA), and India (ISRO). Although there were more mission proposals in the early 21st century, there was a reduction in investment and financial support from governments, which resulted in a decline in the plans for the exploration of the Red Planet. However, in the second decade of the century, companies from the private sector enrolled the "race to Mars" and the interest in exploring this planet increased and restarted with a new strength and willingness to make these projects feasible.

According to the Mars One project website, there are a number of reasons to go to Mars. The first is the realization of an incredible dream. The second is the good old-school curiosity - Where did Mars come from? Can it teach us things about the history of Earth? Is there life on Mars? And, finally, progress. It can be said that humanity's next big step is to send people to Mars. This mission will promote development in different areas, such as recycling, solar energy, food production and in the advance of medical technology (One 2018c).

> *"So much of what drives cosmic exploration involves the quest to learn whether or not we're alone in the Universe - as an intelligent species, or as life at all."* - Neil deGrasse Tyson (quoted in History 2018)

NASA claims that robotic missions have shown similar characteristics between Earth and Mars, but reminds us that there are striking differences that we have yet to understand. The technology required to transport and sustain explorers will lead to innovation in different areas, have long lasting benefits and applications and inspire creative ways to solve problems. The challenge of traveling to Mars and learning how to live there will encourage nations around the world to work together towards this grand achievement. The International Space Station (ISS) is a good example where collaboration is supported and our common interests are embraced (NASA 2018c).

Differences between Earth and Mars

General differences between Earth and Mars can be summarized as: Mars having a diameter of 6790 km, slightly more than half the size of Earth, that has a diameter of 12750 km; nearly 70% of the surface of Earth is covered by liquid water, while in Mars the surface is essentially covered with rock and dust (Sheshpari, Fujii, and Tani 2017); the average surface gravity acceleration on Earth equals to 9,80665 m/s^2, whereas on Mars it is 3,71 m/s^2, (approximately a third of Earth's gravity) which means that a person on Mars would experience 62,5% less gravity than he is used to back home; the temperature range on Earth varies from -88°C to 58°C, with an average temperature of 14°C, and the temperature range on Mars varies from -140°C to 30°C, with an average temperature of -63°C; Earth's atmosphere is over 100 times denser than Mars's atmosphere (NASA 2018b); a day on Mars is only 39 minutes and 25 seconds longer than Earth's, but a Martian year with 687 days is far longer than one on Earth, making seasons twice as long; the orbit of Mars is oval, which means that seasonal variations between winter and summer are more severe than those on Earth (Petranek 2015); Other detailed information about the differences between the two planets can be seen in Table 1.

	Earth	**Mars**
Average Distance from Sun	150 million km	229 million km
Average Speed in Orbiting Sun	29,8 km/s	23,3 km/s
Diameter	12750 km	6790 km
Tilt of Axis	23,5°	25°
Length of Day	23 h 56 min	24 h 37 min
Length of Year	365,25 days	687 Earth days
Temperature range	-88°C to 58°C	-140°C to 30°C
Average temperature	14°C	-63°C
Volume	1,0832 x 1012 km^3	1,63116 x 1011 km^3
Mass	5,9722 x 1024 kg	6,4169 x 1023 kg
Gravity	9,80665 m/s^2	3,71 m/s^2
Atmosphere	78% nitrogen, 21% oxygen, 1% others	96% carbon dioxide, <2% argon, <2% nitrogen, <1% other
Number of Moons	1 (Moon)	2 (Phobos and Deimos)

Table 1 - Differences between Earth and Mars. Adapted from “Mars Facts” (NASA 2018b).

Further characteristics of Mars

The fourth planet in the solar system is named after the Roman god of war, Mars (Latin: *Mārs*, [maːrs]), because the ancients called land of Mars to the red lands from which they extracted iron for weapons. Without knowing it, they were right, because Mars owes its colour (Figure 5) to its rocks that are very rich in iron oxide. Moreover, today we know that the colour variation of the surface is mainly because of the violent winds that blow there (Bon et al. 2000).

Figure 4 - Earth design pantone by the author.

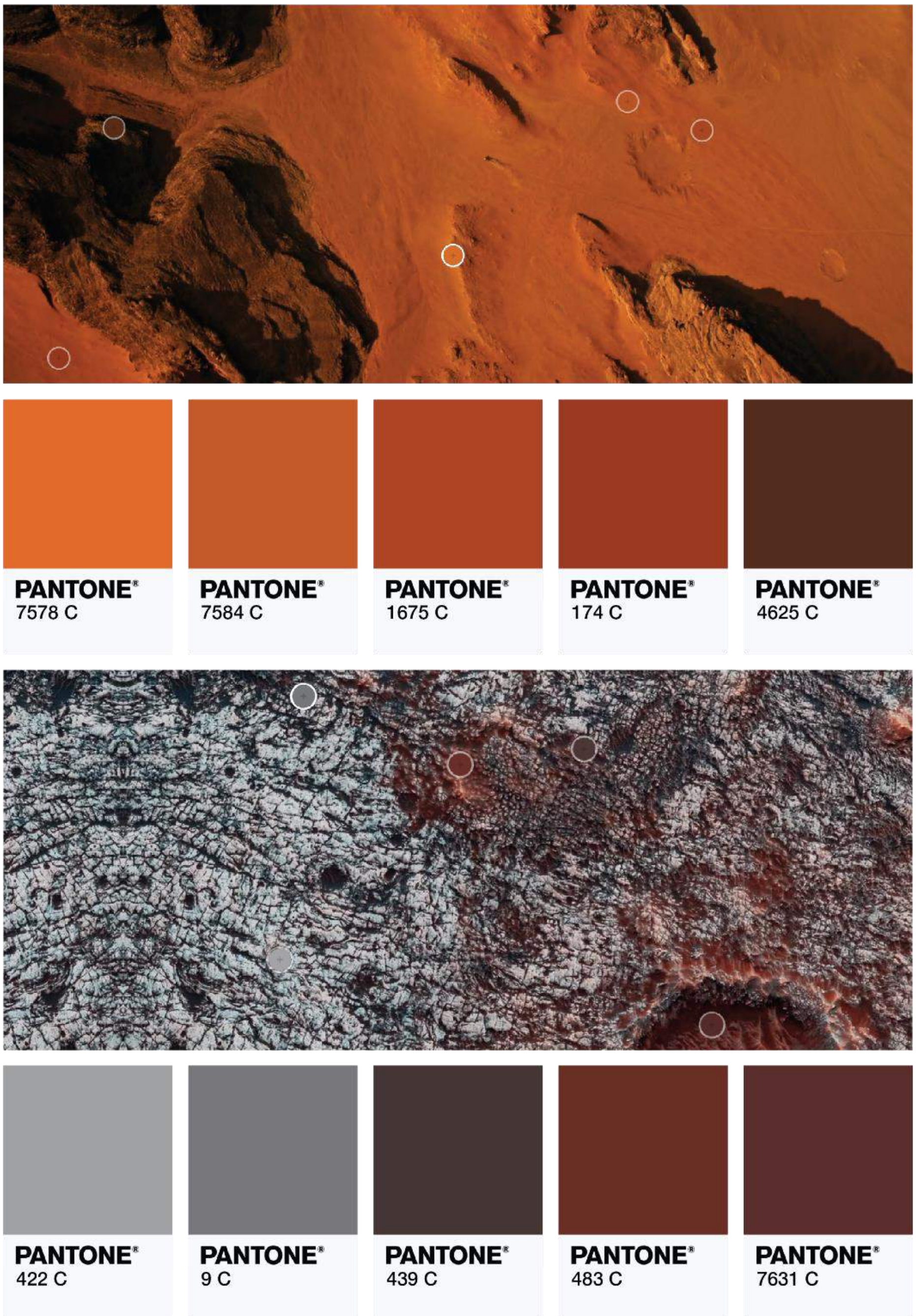

Figure 5 - Mars design pantone by the author.

Topography and ice caps

Studies of geomorphology conducted by orbiters such as MOLA (Mars Orbiter Laser Altimeter) (Sheshpari, Fujii, and Tani 2017), showed that the Northern hemisphere has a low elevation, is flat and has few craters (Figure 6). However, large shield volcanoes can also be found there. As for the Southern hemisphere and the equator, it can be visible dendritic channel patterns, huge flood channels and cratered highlands, a morphology that is totally different from the Northern hemisphere (Bargery et al. 2011). Winds blowing at 200km/h happen in Mars and they move a very thin layer of dust and ice crystals that very slowly corrodes the relief (Bon et al. 2000).

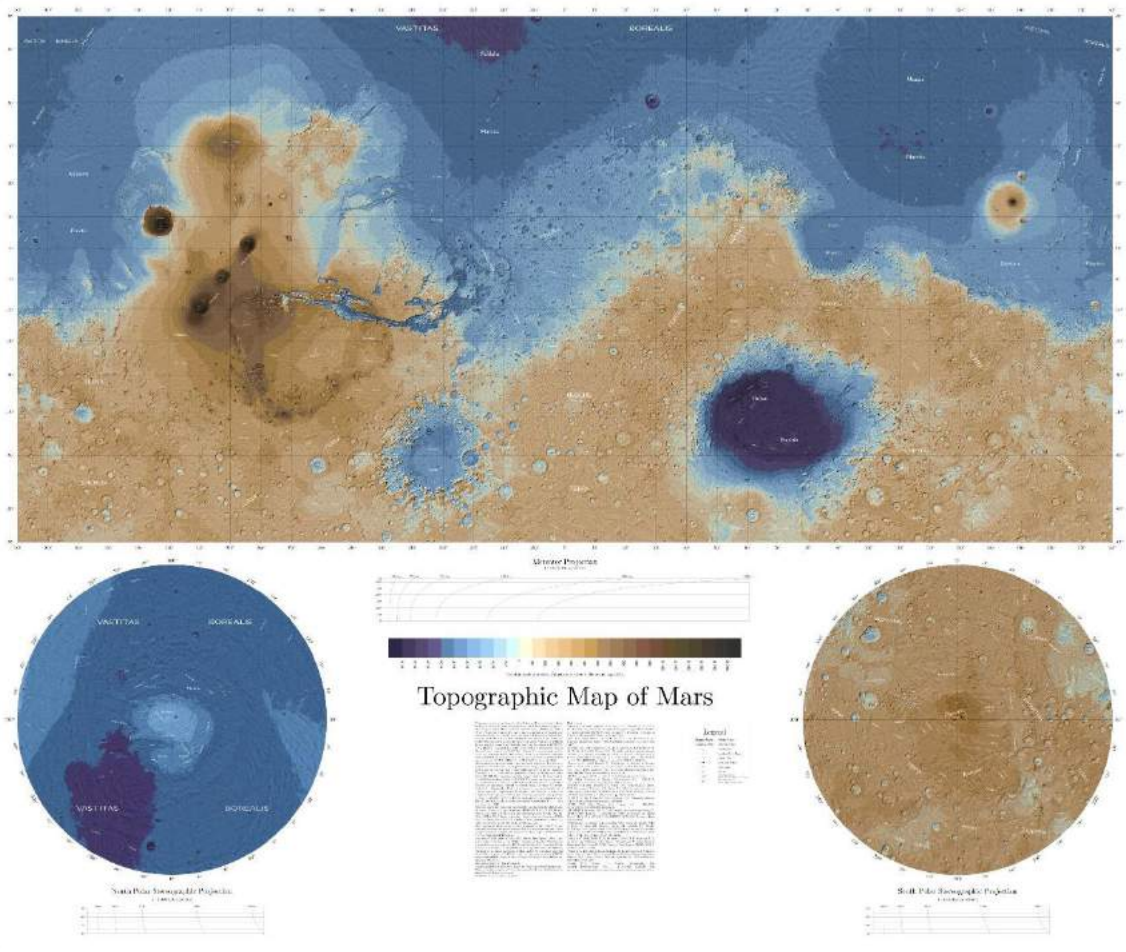

Figure 6 - The Topography of Mars by MOLA (Macháček 2014).

Research on climate and temperature shows that the climate on Mars 3,5 billion years ago was warm and humid, similar to Earth's early days. The reaction between carbon dioxide and water from the atmosphere formed carbonate rocks that consumed most of the CO_2. Because there is no recycling process like Earth's plate tectonics in Mars, it cannot bring back carbon dioxide. Therefore, Mars’s atmosphere is very thin and it has very cold temperatures, resulting in the existence of frozen water in the Martian poles in the form of permafrost or trapped at underground depths (Sheshpari, Fujii, and Tani 2017). But astronomers also think that large quantities of water in the form of ice hide in the Martian sub-soil (Bon et al. 2000).

If Mars suffered a great meteorite bombardment in its youth, many impact craters were destroyed by wind erosion and volcanic activity. Huge currents of lava flowed through the thick crust and covered the plains again. In some localities, they poured layer after layer to form volcanoes over 25km in height, with a 200km in diameter groove. These are the largest of the entire solar system. In other places, the ground fell, opening up crevices, like the channel of *Valles Marineris*. This cavity of collapse is 5km deep, 200km wide and extends over 5000km (Bon et al. 2000).

Main composing rocks

The composition of Mars is similar to Earth's. Its crust and surface is composed mostly of iron-rich basaltic rock; its mantle is composed of silicate rock; and its core is probably an iron, nickel, and sulphur core, but whether it is hot liquid or cooled metal is not known (NASA 2018b).

Data obtained from remote sensing spectral data and meteorites shows that materials from the crust and surface are mainly basaltic or originated from basaltic rocks, mostly as a result of volcanic activities (McSween, Taylor, and Wyatt 2009). The rover Opportunity found also sedimentary rocks in *Meridiani Planum*. Data obtained from these discoveries showed that the surface of Mars has been covered by regolith and basaltic soils (Sheshpari, Fujii, and Tani 2017). The geologic distribution map of the surface of Mars elaborated by the USGS (United States Geological Survey) (Tanaka et al. 2014) can be seen in Figure 7 (complete map in Appendix I).

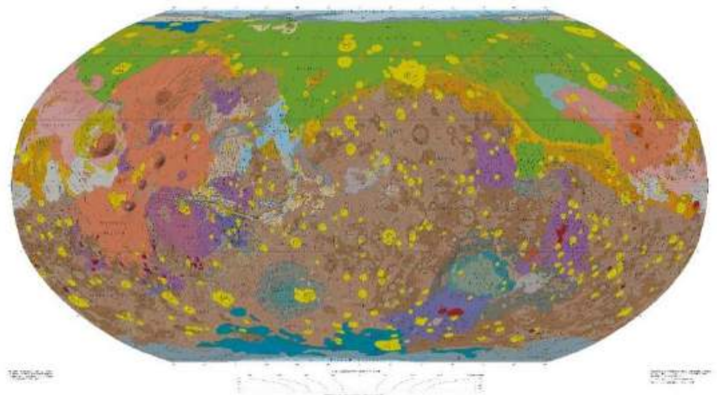

Figure 7 - Geologic Map of Mars by USGS (Tanaka et al. 2014).

From the observation of the geologic map of Mars, it can be concluded that the surface is mostly covered by volcanic rocks (pink, purple, orange and red). However, it can also be seen that sediments in the form of soil exist in the form of low to high thickness layers. In case of rock excavation being necessary for human shelter (an idea proposed by many authors) it can be performed by different transferable equipment including solar or electrical powered machines. These machines can vary in size from hand held drillers to micro or mini sized tunnel boring machines (TBM). The information on the bed rock depth under soil layers is not significant. However, if the rocks are like hard igneous rocks, it would be more practical to use miniature TBMs rather than shield machines (Sheshpari, Fujii, and Tani 2017).

Lava tubes

The Mars Odyssey orbiter has discovered natural caves, or lava tubes, from volcanic rocks like basalt in the equatorial regions of Mars (Figure 8). These caves can be developed or excavated further to provide shelter against radiation and micrometeorites as well as provide space for humans to live in and perform their activities. With the help of miniature or mini TBMs, that can be taken with powerful rockets to Mars, underground space can be developed. These TBMs can be remote controlled from Earth if the required experts are not the first settlers. One possible way to turn these lava tubes into efficient shelters is to use natural Mars' *in-situ* materials combined with additives or binders taken from Earth to seal these spaces and provide insulation against outside temperature (Sheshpari, Fujii, and Tani 2017).

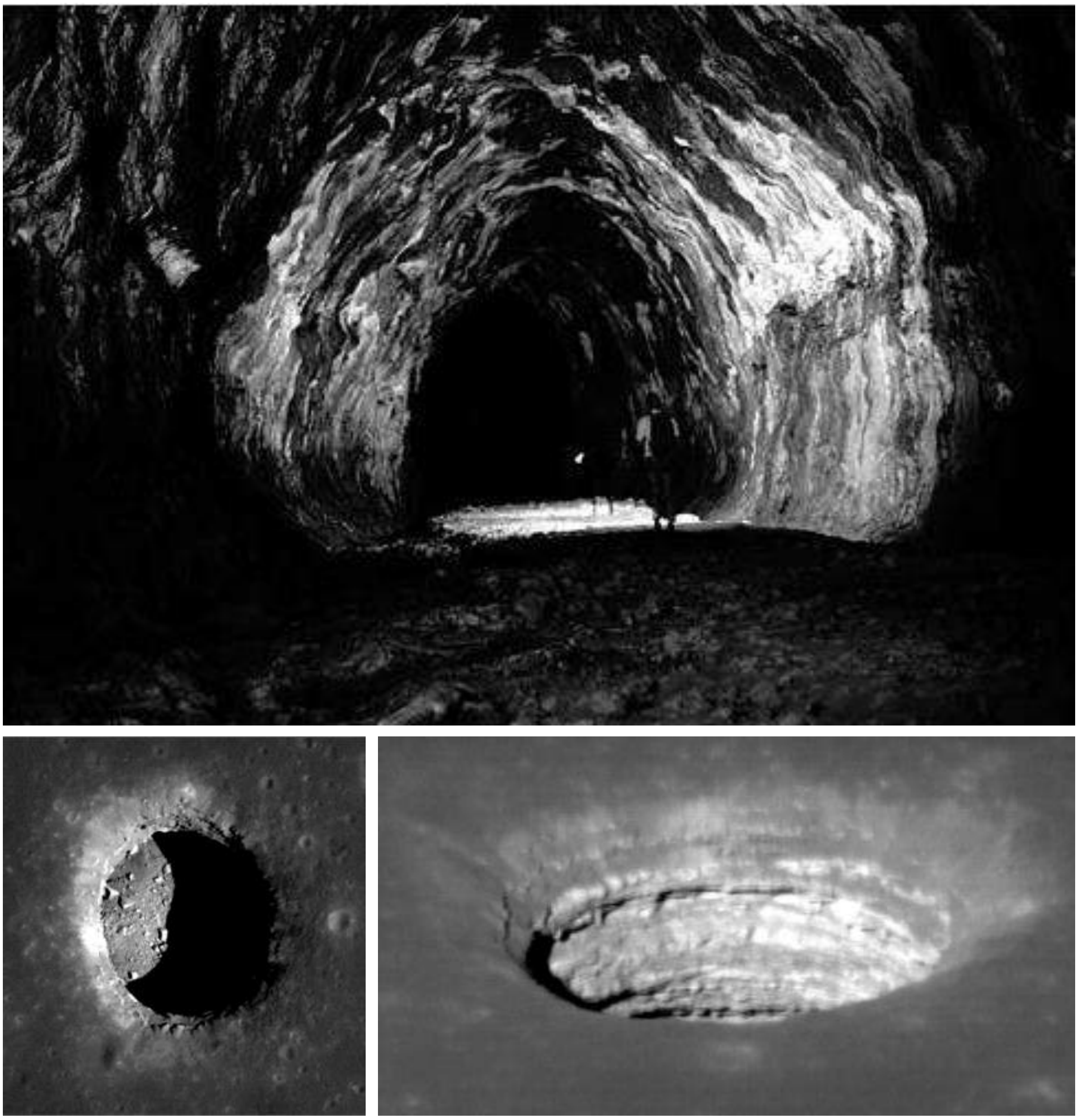

Figure 8 - Top - Lava tube in Australia, on Earth (Kiernan, Wood, and Middleton 2003); Bottom - Lava tube entrance on Mars (NASA 2017).

In-situ resources

The vast distance between Earth and Mars makes it neither possible nor economically reasonable to rely on permanent interplanetary supply. *In-situ* resource utilization (ISRU) will be necessary to reduce the launch mass and the cost of future installations on the Red Planet. Mars provides plenty of raw materials that can be used to establish a lasting, self-sufficient human colony on its surface (Arnhof 2016). As it will later be shown in the chapter 3, many possible solutions that make use of *in-situ* resources, and that are already being explored, will be presented next.

Power

Energy is essential for the functioning of whatever will be built on Mars. Some authors even propose that sufficient amounts of energy and power networks should be guaranteed before human arrival. Solar panels can be used to produce energy, which can be saved by batteries for times where little sunlight is available. (Arnhof 2016). Another suggestion is a microwave power system that can stay in orbit and project generated power to a receiving array on the surface or just a solar array on the surface. It is also important to consider the energy needs of constructing things, producing food and oxygen and other demands of a functioning colony.

Water

Humans need water in order to survive and bringing water from Earth is only viable for the first days of the mission. This means that water will have to be reclaimed from waste, be produced or extracted *on-site*. They can either deploy a ground-penetrating radar to find underground water, and then drill (Petranek 2015) or excavate frozen material and bake it. Microwave beams could be used to vaporize the water ice so it could be collected. This would only require small-scale drilling and little digging (Hsu 2008). However, an even easier method has been proposed by Allen and Zubrin. They suggest that water could be obtained by deploying a transparent tent made of 0,1mm thick polyethylene and using the greenhouse effect occurring within it. The great advantage of this method is the lightness of the tent, making it easy to move to a new field by a rover. This leaves room for the already mined surfaces to rehydrate themselves, making continuous "farming" possible (Allen and Zubrin 2003).

Oxygen and fuel

Per day, a human in space needs approximately 0,84kg of oxygen (Arnhof 2016). Breathable air can be brought with the robotic and astronaut missions, recycled and generated from *in-situ* materials (Kading and Straub 2015). A Sabatier[1] reactor could produce oxygen for the crew's needs (Allen and Zubrin 2003).

[1] The Sabatier Process is a simple, scalable and energy efficient way to produce methane, oxygen and water for fuel and life support on-site that could be used to minimize launch mass and cost. The reaction involves carbon dioxide (CO_2) from the Martian atmosphere and hydrogen (H_2), from Earth or Moon or produced on the Martian poles. $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O \rightarrow CH_4 + O_2 + 2\ H_2$ (Allen and Zubrin 2003)

Additional oxygen and fuel could be produced by cyanobacteria and algae, which can grow in the greenhouse for dietary supplementation (Verseux et al. 2015).

Food production

Although in the beginning food will be brought from Earth, interplanetary astronauts will have to build greenhouses for plants and food production. An artificial eco-system will enable crews to grow fresh products to supplement their nutrition and will also create oxygen and absorb carbon dioxide. In those green spaces, astronauts not only see plants growing and literally harvest the fruits of their effort, but also smell, taste and feel the presence of vitamins in the plants, which benefits the physiological and psychological health of the explorers. The greenhouse is very important for the self-sufficiency of a colony. Once the base has more inhabitants, more and bigger greenhouses will be necessary (Arnhof 2016) where robots can be used to harvest the crops (Kading and Straub 2015).

Regolith

Regolith is the material derived from the layer of unconstrained rock material covering the Martian surface. As it will later be seen in chapter 3, many authors have proposed the use of Martian regolith for the construction of structures and cosmic and solar radiation shielding. Concepts of 3D printers that print with raw Martian regolith have also been presented.

At first, habitats could be covered with bags filled with unprocessed regolith (in its original form) or simply be "buried" under it. The bags provide an easy, quick and flexible method of shielding (Arnhof 2016). Later, when more permanent structures are necessary, the processing of regolith should be considered, to improve practicability and shielding efficiency. Bricks made from regolith can be used for construction as well as also serve as protection against the cold temperature from the outside (Petranek 2015).

Sen, Carranza and Pillay suggest a composite material made from Martian regolith with polyethylene (PE) as a binder, synthetized from the Martian atmosphere, for effective radiation shielding and sufficient structural and thermal integrity (Sen, Carranza, and Pillay 2010).

Arnhof proposes a concrete made from processed regolith that can be reinforced with basalt fibre meshes or loose basalt fibres, to improve mechanical properties (Arnhof 2016). Basalt can be found in large quantities all over Mars. It would simply need to be melted and drawn into fibres (Tucker and Ethridge 1998). Robotic rovers would process the ground regolith, the powder binder and the basalt fibres into fibre concrete and use a printer head (Arnhof 2016).

A. Scott Howe and his colleagues presented a concept for 3D-printing construction using regolith from the Moon and Mars. Instead of sintering the regolith it could be used to make some sort of fibre concrete (Howe et al. 2015). This would allow, for example, the creation of shells to lay over the habitats for additional shielding (Arnhof 2016).

Rocks

The use of rocks for shelter recalls prehistory, where humans used caves and excavations to protect themselves from the environment. In Mars, the use of rocks will also be intelligent. Sheshpari, Fujii and Tani presented an idea of excavating surficial rocks and isolating excavated space with insulation material (Sheshpari, Fujii, and Tani 2017).

Sulphur

Studies of Martian meteorites and Martian surface deposits show high levels of sulphur (King and McLennan 2010). Since sulphur concrete is used as an infrastructure material on Earth since the ancient times, the authors Wan, Wendner and Cusatis defend that it can also be used for space construction. After stepping on the Moon, NASA and collaborative researchers, starting in the early 1990s, studied and developed lunar concrete using molten sulphur. Now, the authors propose the development of a recyclable Martian concrete using 50% of Sulphur and 50% of regolith. (Wan, Wendner, and Cusatis 2016).

Basalt

As mentioned in the subchapter *Why Mars*, basalt (Figure 9) is abundant on the Red planet and present across the whole surface (McSween, Taylor, and Wyatt 2009). It is an extrusive igneous rock that is commonly formed by magma extrusions during a magma flow and is typically dark coloured - grey or black. It is composed of 45-53% of silica and is rich in iron and magnesium (Survey 2015). When in comparison, numbers show that basalt is more elastic than steel and has similar elasticity to aluminium. It also has a stress level breaking point in the range of some plastics, such as low density and high density polyethylene. It also has radiation resistance, a very high specific heat and a very low permeability constant, so it appears suitable for use in pressurized structures (Kading and Straub 2015).

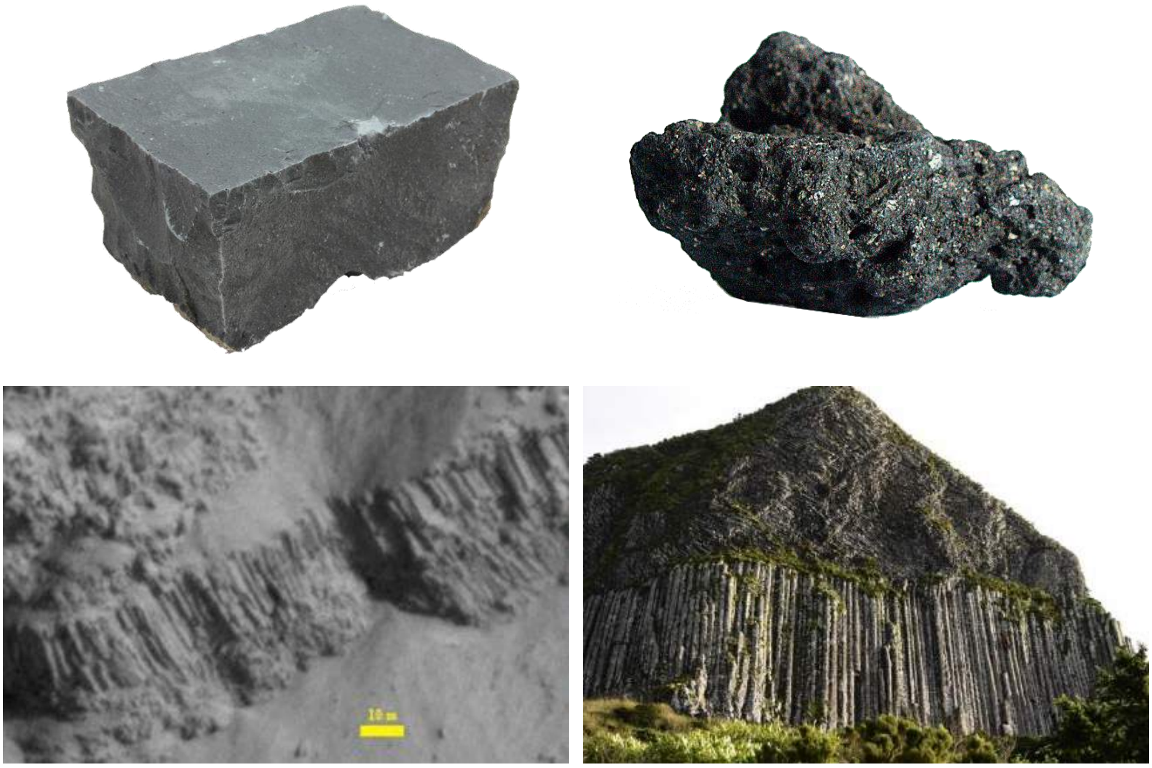

Figure 9 - Top – Basalt stone; Bottom left - Columnar jointing on Mars (Geology.com 2018); Bottom right - Columnar jointing in Azores Island, on Earth (Montanheiros 2017).

"Anyone who watched Neil Armstrong set foot on the moon in 1969 can tell you that, for a moment, the Earth stood still. The wonder and awe of that achievement was so incomprehensible that some people still believe it was staged on a Hollywood set. When astronauts stepped onto the moon, people started saying, «If we can get to the moon, we can do anything." They meant that we could do anything on or near Earth. Getting to Mars will have an entirely different meaning: If we can get to Mars, we can go anywhere." - Stephen Petranek in the book *How We'll Live on Mars* (Petranek 2015).

Figure 10 - Astronaut in space. Image retrieved from the TV series *Mars* from National Geographic Channel (Bormanis, Fisher, and Janszen 2016).

Plans for exploration and colonization of Mars

Many space agencies and private organizations have announced plans to send humans to Mars in the near future (Arnhof 2016). This planet has been the focus of space exploration in the last decades and one of the most discussed subjects of the present time. The development of any space mission inherently brings together previous work from various disciplines (Kading and Straub 2015). There are a number of completed and ongoing projects that involve various areas - such as engineering, design, architecture, biology, psychology, philosophy, among many others - and multidisciplinary teams with the goal of exploring the planet Mars and eventually colonizing it. Simulators on Earth and spaceflight analogous environments make it possible to test design solutions prior to their deployment in space.

Some of the most important projects are the *Mars One* project, the *Mars 500* project, the *Mars Direct* project, *Falcon Heavy* rocket from SpaceX, the NASA's *Journey to Mars* project, the *3D-Printed Habitat Challenge Design Competition* contest launched by NASA, and the *Mars Science City* project. Together with others no less important, some of the most relevant projects were divided in three categories according to their focus: plans that are previous to human arrival on the planet, plans for the moment when mankind sets foot on Mars and plans for a time when a viable settlement is achieved and expansion is the next goal.

Before human arrival

Mars 500 (Mars-500 2018), is a project that was developed during the period of 2007 to 2011 by Russia together with ESA (ESA 2018) and China. It aimed to conduct a psychosocial isolation experience in order to prepare a future crew for Mars. The *Mars Direct* project (Society 2018) is a plan developed by Dr. Robert Zubrin (Zubrin, Baker, and Gwynne 1991) with the goal of exploring the planet Mars with a minimalist approach allowing maximum results with minimal investments. Another project that simulates life on Mars is the *Mars Science City Project* (Figure 11). It started in 2014 and is still being developed by the architects of the *Bjarke Ingels group* in the United Arab Emirates. It consists of a huge city of space simulation, where life on Mars will be simulated. A series of monumental dome structures will contain laboratories for energy and water testing, agricultural testing and food safety studies, and a museum that will exhibit the greatest space achievements of mankind. The walls of the museum will be manufactured by 3D printing, using desert sand from the Emirates (Group 2018).

Figure 11 - City of simulation of life on Mars being developed by the Bjarke Ingels group (Group 2018).

For architects and designers, the goal is to design environments that support their occupants physically, psychologically, socially, and spiritually. Habitability entered NASA's vocabulary during the mid-1970s, when they had to design *Skylab* not only to be operated but to be lived in (Harrison 2009). Further improvements evolve from a mix of habitability studies, crew debriefs, aesthetic experimentation, and evaluation (Mohanty, Jørgensen, and Nyström 2006). The first fifty years of space exploration has been marked by the increase of crew size, from one to half a dozen or more; crew diversity, men and women from different professions and nationalities; mission duration, first measured in hours and days and now measured in weeks and months; and partnering with robots (Harrison 2009).

Many Mars missions tend to propose a preliminary payload landing, while communication satellites in orbit relay communications (Kading and Straub 2015). In the *Mars Direct* project, Robert Zubrin propose the launch of an unmanned module as a precursor to begin converting the Martian atmosphere into rocket fuel, followed by a manned mission (Zubrin 2011). The *Mars One* project also utilizes robotic precursors, but its following manned missions are one-way (Kading and Straub 2015). The *SpaceX* company has been developing rockets, such as the *Falcon Heavy* rocket (SpaceX 2018a) which is designed to transport cargo and to possibly transport humans to Mars by 2024 (SpaceX 2018b).

Obviously, there are still a lot of technological and engineering hurdles to overcome until the first humans can set foot on Mars. For the space explorers, such an enterprise will be physically very demanding. They will experience severely different environments from Earth (1g) to space (0g) to Mars (0,38g). The need to protect humans from the harsh environmental conditions of Mars (ionizing radiation, atmospheric pressure and composition, temperature) and the psychological and sociological impact of prolonged isolation and confinement increase the complexity and risk of such missions (Arnhof 2016).

Marlies Arnhof, a student from the Master in Architecture at the Vienna University of Technology, reflects on the first steps of the Martian exploration, before the arrival of humans. In his article, he supports preliminary automated exploration done by robots. He says that the use of robotics for cargo will be an important element for a Mars base, as well as the use of pressurized rovers that can house astronauts for weeks, support people in case of an emergency and be directly docked to the habitat. Before the arrival of the first crew, he lists the sending of a habitat with a suitport[2] and a greenhouse, two pressurized rovers, a cargo handling rover, Sabatier process hardware, power generators, a water extraction unit and an ascent module for Earth return. Regarding energy he advocates that sufficient energy on site is a prerequisite. Humans will need a reliable and durable power system that is already in place and working, before they even start their journey to Mars.

When the robotic exploration rovers find the perfect place for the first manned mission to land and the communication satellites are in place and working properly, automated site preparation can start. Shortly before the crew arrives, the habitat sent from Earth will be carried by the robotic rover to the base site and will be deployed there. As soon as enough power, fuel and life support is generated, it is safe enough for humans to land on Mars (Arnhof 2016).

Benjamin Kading and Jeremy Straub, from the University of North Dakota, also suggest unmanned preparation missions to Mars prior to human arrival. They say that these missions would build the infrastructure required to support human life. In order to reduce mission launch and deep space transfer mass and volume, they defend the fabrication and 3D printing of most of the base structures from *in-situ* resources. Upon the landing, the spacecraft would be unloaded and the first phase of 3D printing would start by printing components of the main dome. Once the main dome is completed, they suggest the construction of a basalt 3D printer. This printer would create the living dome structures to create a base. Then they propose sending humans to Mars. However, they emphasize that this mission concept is not intended as an initial human mission to Mars, but instead as a longer term and larger scale successor mission once several initial missions have been completed. Among the key mission elements that are required for sustaining life, power could potentially be provided by a microwave power system that will stay in orbit and project generated power to a receiving array on the surface – which reduces the amount of mass that must be landed - or a solar array on the surface; water

[2] Alternative technology to an airlock.

would be initially brought from Earth and then reclaimed from waste and generated from *in-situ* resources; food would grow in greenhouses and harvested by machines; breathable air would be brought with the robotic mission and the later astronaut missions, recycled and generated from *in-situ* materials. (Kading and Straub 2015).

First steps on Mars

First on the astronaut's punch list is the construction of a base camp habitat. After analysing multiple historic missions, Bret G. Drake (Drake 1998) concludes that astronauts require 90m^3 of space per individual for long-term missions. However, his analysis also suggests that significantly smaller volume can be utilized for shorter periods. The short-term missions such as *Mercury*, *Voskhod*, *Vostok*, *Gemini*, *Apollo LEM*, *Apollo CM* and *Soyuz* had all less than 10m^3 per person for periods less than 15 days. The space shuttles conducted longer missions and had just over 10m^3 per individual (Kading and Straub 2015).

Similar construction materials to Earth's are scarce in the Red planet, which makes providing shelter with habitable conditions for humans difficult (Sheshpari, Fujii, and Tani 2017). Many authors propose shelter built underneath the surface of Mars.

Sheshpari, Fuji and Tani, professors and students from universities of Canada and Japan, recommend underground structures as the primary shelters for humans to live in. The main reason why they suggest this is because Mars has lack of atmosphere and magnetic shielding, meaning that humans would be exposed to high levels of radiation from cosmic rays. This is crucial because long-term exposure to galactic cosmic rays (GCR) and particles released in sudden solar particle events (SPE) can result in cancer and death (Reitz, Berger, and Matthiae 2012). Hence, for human survival, habitat structures that meet both radiation shielding and structural requirements is mandatory (Sen, Carranza, and Pillay 2010). The GCRs and strong SPEs result in gamma rays and neutrons that can break molecular bonds in the Martian soil (Gifford 2014). Neutron is the most penetrating radiation in Mars and it can be stopped by 5–10 t/m^2 mass. This means that 2-4 m of overburden rock is enough to stop its penetration. Therefore, they suggest the excavation of surficial rocks, with micro or mini sized TBMs, and then isolate the excavated space with insulation material to provide habitable heating conditions (Sheshpari, Fujii, and Tani 2017). Before them, Fogg (Fogg 1996) and Cushing (Cushing et al. 2007) have suggested that Mars settlers in early days can use the natural caves or lava tubes found on the *Arsia Mons* volcano, placed on the equatorial regions. With geothermal energy at their disposal (Fogg 1996) humans can excavate further and build shelter against radiation and micrometeorites. These shelters can be sealed with the use of natural *in-situ* materials, combined with additives or binders taken from Earth to protect against outside temperature (Sheshpari, Fujii, and Tani 2017).

Benjamin Kading and Jeremy Straub suggest a two-in-one concept. They say that, collecting basalt, producing structures and deploying structures should be concurrent. In this way, some of the areas that are mined for the extraction of basalt could be used to house cylindrical underground units. On top of these underground units, surface units can be placed and latched to. This concept encourages the reuse of the basalt mines as well the share of the excavation expense between the basalt extraction and structure deployment process. Additionally, these underground structures will benefit from the insulation and resistance to radiation from the surroundings (Kading and Straub 2015).

Other authors propose dwellings for the surface of Mars. As mentioned before, Marlies Arnhof suggests a basic base (Figure 12) sent from Earth to be set up on the surface of the planet by robots. Following the landing, the crew will take the pressurized rovers to get to the spot where the habitat is already waiting for them. After settling in and establishing the base with a small greenhouse, the spacefarers have to research and explore factors that determine if a settlement on Mars can be viable and if such an enterprise would be scientifically and economically reasonable. The next steps will be small scale drilling with the help of the rovers and surface mining. They will also have to do feasibility studies on the ISRU production of food and construction materials, namely regolith, basalt fibres and polymers. Meanwhile the Sabatier unit will go on producing fuel and life support elements.

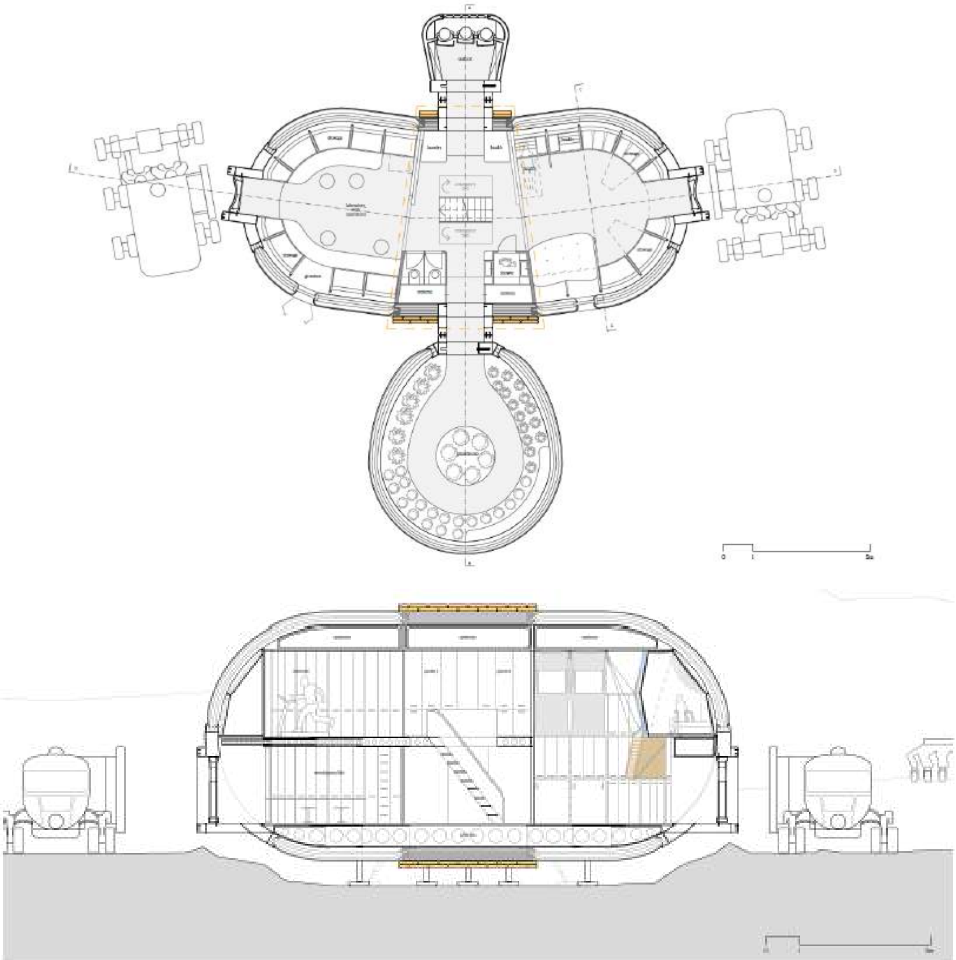

Figure 12 - Basic habitat design by Marlies Arnhof for early Mars missions (Arnhof 2016).

Even inside the very well shielded habitat, astronauts are exposed to cosmic and solar radiation, therefore, he suggests additional radiation shielding to further reduce the radiation doses. A launch-mass-saving option is the use of regolith. For the first missions the easiest way to protect against radiation would be to use regolith in its original form. The habitat could be simply 'buried' under it or covered with regolith-filled bags. The bags have the advantage of being flexible and portable. Then, other cargo ships can deliver more habitats, inflatable connecting halls, more pressurized and robotic rovers with tools and more infrastructures. Crews will live in extreme environments and will live isolated and confined for much longer periods of time than ever before. Thus, the design of the habitats require careful consideration of physiological and psychosocial conditions of living in space. To optimize living and working conditions, the base would respond to the environment and the residents' number and needs, meaning that it would evolve and grow continuously. Adaptability and flexibility in the interior of the habitat would enable the crew to reconfigure the space according to their needs and living preferences. Then, an elementary surface base could evolve into a settlement and gain increasing self-sufficiency by using local resources (Arnhof 2016).

Mars One (One 2018b) is an organization that proposes to land the first humans on Mars and establish a permanent human colony until 2032. It has begun training selected astronauts since 2017 and plans to send rovers, satellites, six units for the explorers to live in and the explorers themselves (Figure 13).

Figure 13 - A six-unit colony proposal by the Mars One foundation for Mars (One 2018a).

The mission concept by Benjamin Kading and Jeremy Straub, mentioned in the previous chapter, continuous with the landing of multiple astronauts to inhabit the structures built by the robots from the first mission. These structures are also planned to be built on the surface of Mars (Kading and Straub 2015).

There is also the concepts presented by the author J. Kozicka (Kozicka 2008), where he proposes an alternative to the use of lava tubes, with easy access to sunlight and a concept of terraces on the relief where underground habitats would be excavated (Figure 14).

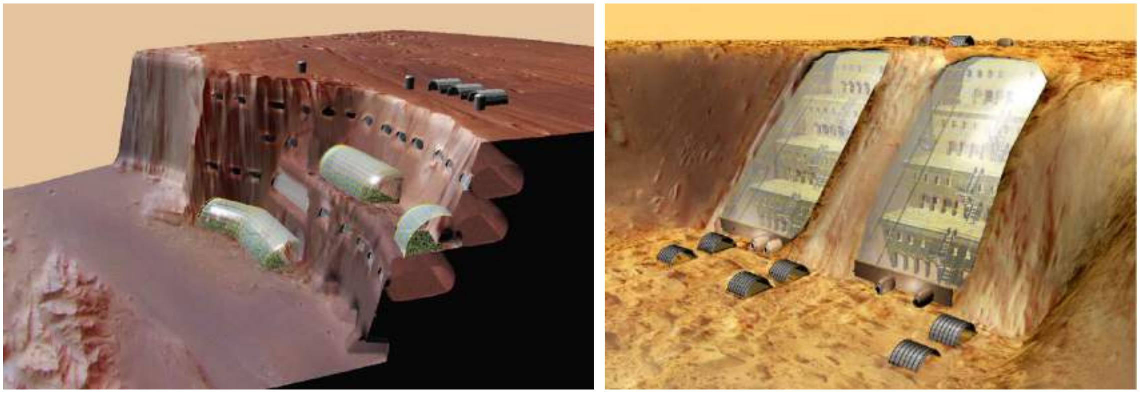

Figure 14 - Alternative concepts to the use of lava tunnels proposed by J. Kozicka (Kozicka 2008).

Stephen L. Petranek also suggests a first base brought from Earth deployed on the surface of the planet. He adds that astronauts must also inflate “buildings” – domed pressurized tents made of exotic materials that will increase their living area and act as greenhouses in which to grow food. Then, these astronauts should build more permanent structures, possibly out of bricks they make from the regolith, before other ships arrive with more people. He advocates that landing near the equator allows explorers to take advantage of milder temperatures that can reach 21 degrees Celsius on a summer day. However, at night the temperature easily reaches minus -73 degrees Celsius, therefore structures will need to protect inhabitants from the cold as well as to protect them from the radiation (Petranek 2015).

After the preliminary base is built, astronauts must begin a very important task: to find water. They must find out if there is, as NASA landers and orbiters have predicted, enough water in the surface to support their hydration needs and serve as a stock to make more oxygen to breath. If they do not find water on the surface they have to deploy a ground-penetrating radar to find underground water, and then drill (Petranek 2015). According to Jeremy Hsu, in order do mine water on Mars, it is necessary to excavate frozen material and bake it. He adds that microwave beams could be used to vaporize the water ice so it could be collected and that it would only require small-scale drilling and little digging (Hsu 2008). However, an even easier method has been proposed by Allen and Zubrin. They suggest that water could be obtained by deploying a transparent tent made of 0,1mm thick polyethylene and using the greenhouse effect occurring within it. The great advantage of this method is the lightness of the tent, making it easy to move to a new field by a rover. This leaves room for the already mined surfaces to rehydrate themselves, making continuous "farming" possible (Allen and Zubrin 2003).

Oxygen production will also be on the first to-do lists when humans arrive to Mars. Per day, a human in space needs approximately 0,84kg of oxygen (Arnhof 2016). Allen and Zubrin propose the use of a Sabatier reactor to produce enough oxygen for the crew’s needs (Allen and Zubrin 2003). Additional oxygen and fuel could be produced by cyanobacteria and algae, which can grow in the greenhouse for dietary supplementation (Verseux et al. 2015).

Although in the beginning food will be brought from Earth, interplanetary astronauts will have to build greenhouses for plants and food production. An artificial eco-system will enable crews to grow fresh products to supplement their nutrition and will also create oxygen and absorb carbon dioxide. In those green spaces, astronauts not only see plants growing and literally harvest the fruits of their effort, but also smell, taste and feel the presence of vitamins in the plants, which benefits the physiological and psychological health of the explorers (Arnhof 2016).

In general, it is common to all the projects mentioned:

- Cost reduction, making the maximum with the minimum
- Use of *in-situ* resources that Mars has in abundance and that can be used in the construction of shelters and objects
- Landing of robots before humans in order to build bases and prepare their arrival
- Concepts of 3D printers that print with raw material on Mars, such as regolith and basalt

Regarding the design of housing concepts for Mars, some general objectives can be outlined (Kozicki and Kozicka 2011):

- Large and flexible living spaces
- Private space with possibility of customization for each crew member
- Contact with sunlight, landscape and nature
- Separate the different areas - work and leisure, noisy and quiet spaces, etc.
- Ability to move walls for interior rearrangement
- Capability of base expansion by adding additional modules
- Easy transportation and deployment
- Automatic deployment process (which can be completed by humans)

Advanced future plans

At this point, if it has been established that further human exploration and settlement of Mars is reasonable and viable, more people will be sent to Mars. The settlement should be expanded, using planetary resources. The fibre concrete can be used as main *in-situ* construction material. Marlies Arnhof highlights that, to facilitate rearrangement and enable the crew to configure the space according to their own living preferences, the habitats should be flexible and adjustable for reconfigurations to be made at any time. In his article he shows a more advanced habitat arranged around a central space that functions as an agora, in order for people from different crews to meet frequently and conduct exercise activities (Figure 15).

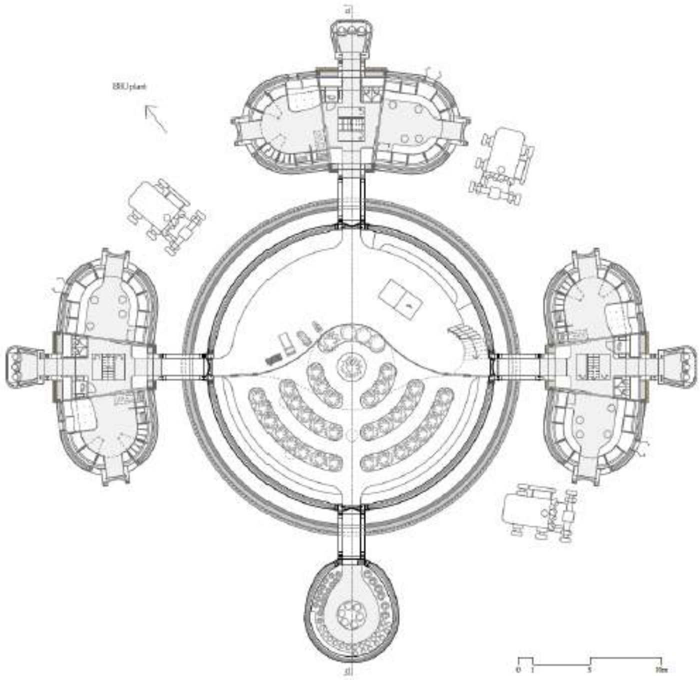

Figure 15 - Advanced habitat design by Marlies Arnhof for a further future (Arnhof 2016).

This arrangement of space helps people bonding with each other, people from different habitats. He also states that greenhouses are crucial for the self-sufficiency of a colony where the valuable psychological benefit, technological development and innovation and constantly improving plant-growth efficiency are present. In the future, once the base has more people, it will make sense to add large scale, low pressurized greenhouses to make use of the carbon dioxide in the Martian atmosphere and lower energy needs. Although the use of robots for farming larger greenhouses is effective, people of every habitats can work together in those places for the good of the community (Arnhof 2016).

Plantations would be in charge of extracting oxygen from the atmosphere and provide food to settlers and domestic animals. Solar panel fields could provide the energy needed to deploy factories (Bon et al. 2000).

After a while, new equipment and replacement parts will be necessary. A way to reduce transport risks and costs is to manufacture them *on-site*. A. Scott Howe and his colleagues developed a concept for a freeform additive construction system (FACS) for the lunar surface, based on ATHLETE[3]. The FACS system is a concept for 3D-printing construction elements made of solar/microwave sintered regolith (Howe et al. 2015). In extended Mars mission scenarios, the ATHLETE-like rover can also be used for building with regolith. It can be equipped to dig and grind regolith but, instead of sintering it, it could make some sort of fibre concrete from *in-situ* resources. This would allow the creation of shells to lay over the habitats for additional shielding of GCR (Arnhof 2016). The concrete made of processed regolith can be reinforced with basalt-fibre-meshes or loose basalt fibres, to improve mechanical properties. Basalt can be found in large quantities all over Mars. It would simply need to be melted and drawn into fibres (Tucker and Ethridge 1998).

In an even further future, when it is established that the base is working successfully and that it is strong enough to sustain itself, more and varied bases can be developed. First those would be built in the proximity of the original base, but at later stages outposts in new, scientifically interesting places would be possible and increase scientific exploration. From now on the settlement should evolve continuously and become increasingly independent from Earth. In the ultimate far future, it should culminate in the settlement reaching independence from Earth and becoming a self-sufficient colony (Arnhof 2016).

SpaceX has also developed concepts to build a thriving city and, eventually, a self-sustaining civilization (Figure 16 and 17). NASA plans to go to Mars and return in 2030 (NASA 2017) and Russia as well.

[3] ATHLETE (All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer) is a versatile cargo handling system developed for lunar exploration by NASA JPL. Every one of its six limbs can be operated independently. It can carry payloads of up to 14 500 kg in Earth's gravity and it is capable of carrying whole habitats on its platform. It can be equipped with a drill, scoop, gripper, hook and line, and various other tools (NASA 2018a).

Figure 16 - Mars city proposed by SpaceX (SpaceX 2018b).

Figure 17 - Colony proposed by the company SpaceX for Mars (SpaceX 2018b).

Another "dreamy", but talked about, project is the terraformation of Mars. The first explorers, alone on planet that appears to have no life, 250 million miles away from home, have everything in common with the great explorers that throughout history scaled mountains and sailed oceans to create new lives. Those who will go to Mars are the beginning of the ambitious plan of terraforming the entire planet - to make its thin atmosphere of carbon dioxide rich enough in oxygen for humans to breathe, to raise its temperature, to fill its empty lakes with water again, and to plant foliage that can flourish in its temperature zone on a diet rich in CO_2. These envoys will set in motion a process that might not be complete for a thousand years but will result in a second home for humans. Like many other frontiers previously overcome, this one will eventually rival the home planet in resources, standard of living, and desirability (Petranek 2015).

Some astronomers believe that long ago the planet Mars was much warmer, had a denser atmosphere and offered favourable conditions for the appearance of primitive life forms. So far, no evidence of current or past biological activity has been found, nonetheless biologists continue their investigations. They discovered in Earth organisms that lived in conditions that we considered harmful to the whole way of life. Thus, some bacteria are capable of withstanding temperatures above 250°C. At the bottom of the seas, beneath enormous pressures, an entire ecosystem was organized around sources of water superheated at 400°C and saturated with hydrogen sulphide. In the Himalayan massif, the plants reach heights of more than 5000m of altitude, managing to create around them their own micro ecosystem. One day it may be possible to change these ultra-resistant terrestrial organisms to adapt them to the current conditions of Mars.

Over time settlers will adapt to Mars instead of Mars adapting to settlers. As the gravity on Mars is about a third of Earth's gravity, they would be three times lighter. To support their weight, the skeleton would not need to be as solid. If children were born on Mars, they would develop differently than on Earth. They would undoubtedly be very large and fragile, and unless we accustomed them to always carry heavy loads, they would have many difficulties coming to live on Earth. From generation to generation, they would differentiate themselves from the human species, eventually ending up becoming true Martians (Bon et al. 2000).

According to Stephen L. Petranek, the ultimate goal of going to Mars is to establish a society that maintains a system of spaceports for rockets, allowing easy lift-off from a planet with low gravity. From those ports, humans can travel to other places, including to the outer reaches of the solar system (Petranek 2015).

Other projects for the exploration and colonization of Mars

NASA has launched the "3D-Printed Habitat Challenge Design Competition" (NASA 2016) to promote the imagination and creation of possible habitats for Mars using 3D printing and *in-situ* resources. The first prize (Figure 18) was awarded to the team that designed a habitat printed with ice (House 2015). The second prize (Figure 19) was awarded to a team that mixed basalt fibres with bioplastic (Spacefactory 2018) and the third prize was attributed to the team that designed a habitat (Figure 20) printed with lava and regolith (LavaHive 2015).

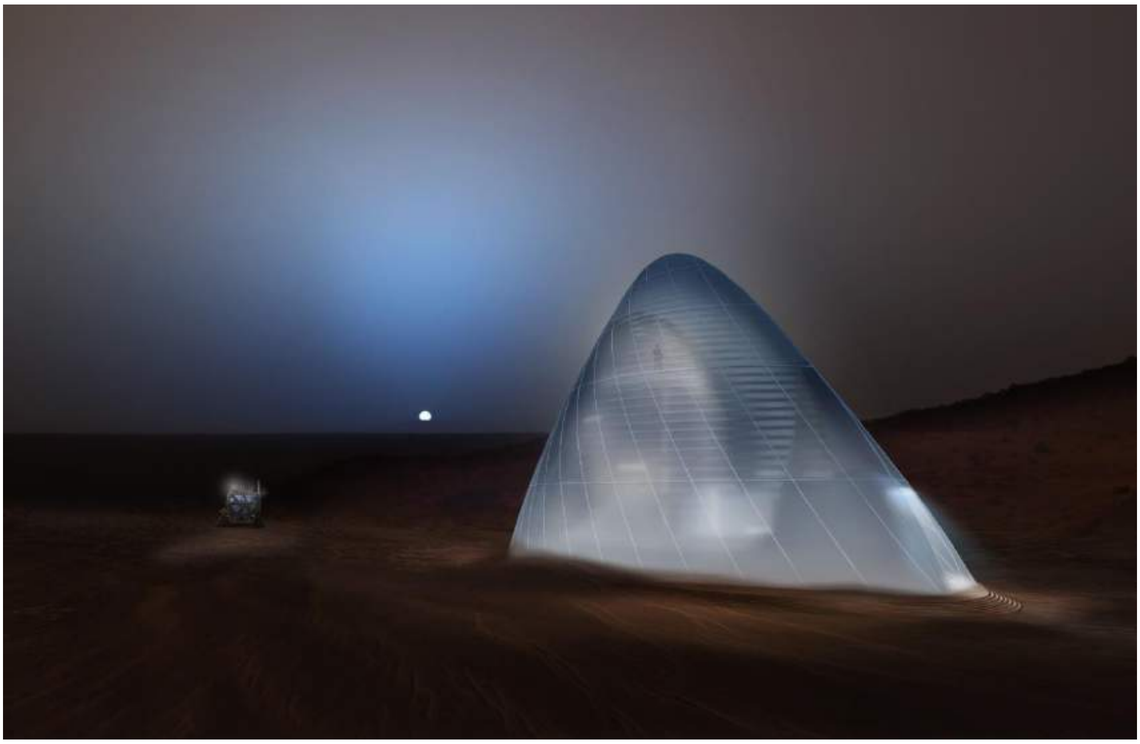

Figure 18 - "Mars Ice House", winning project of the contest launched by NASA "3D-Printed Habitat Challenge Design Competition" (House 2015).

Figure 19 - "MARSHA", project awarded with the second place in NASA's "3D-Printed Habitat Challenge Design Competition" (Spacefactory 2018).

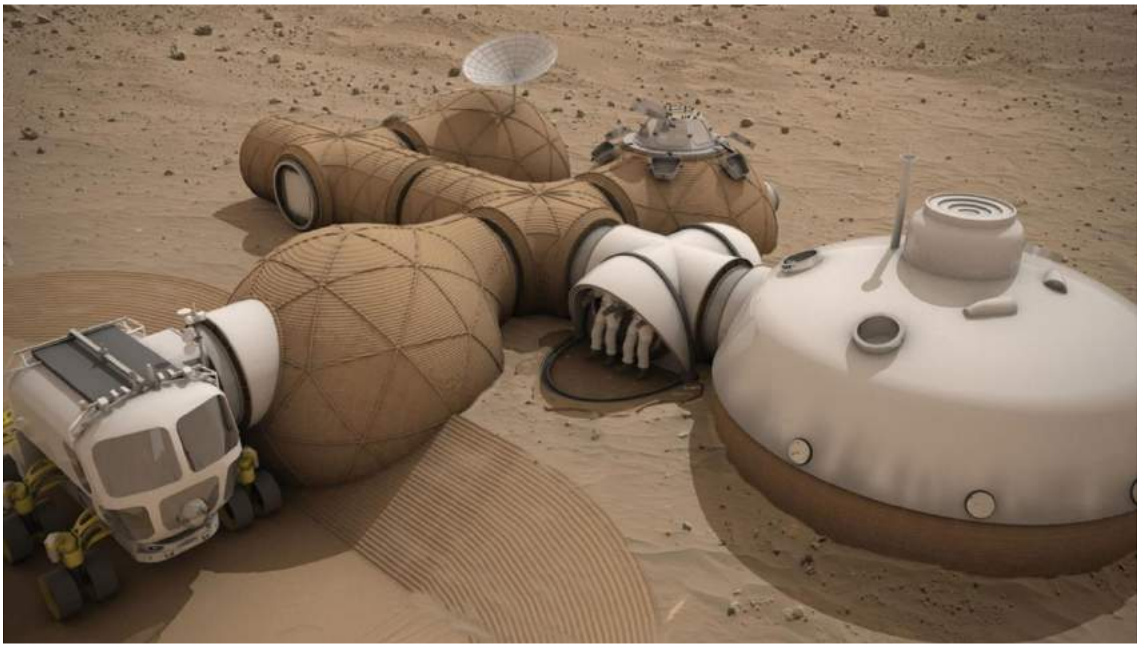

Figure 20 - "LavaHive", project awarded with the third place in NASA's "3D-Printed Habitat Challenge Design Competition" (LavaHive 2015).

Projects that are not related to Mars but are relevant

Design

A few examples of the book *Italy: the new domestic landscape* (Ambasz 1972) are relevant to present here since the design program is much alike the Mars design program. These projects, made by Italian designers, show collapsibility, adaptation and mobility applied to an everyday home and reduces the living requirements to the essentials while saving a maximum amount of space (Figures 21, 22 and 23).

Figure 21 - "Total furnish unit" by Joe Colombo (Ambasz 1972).

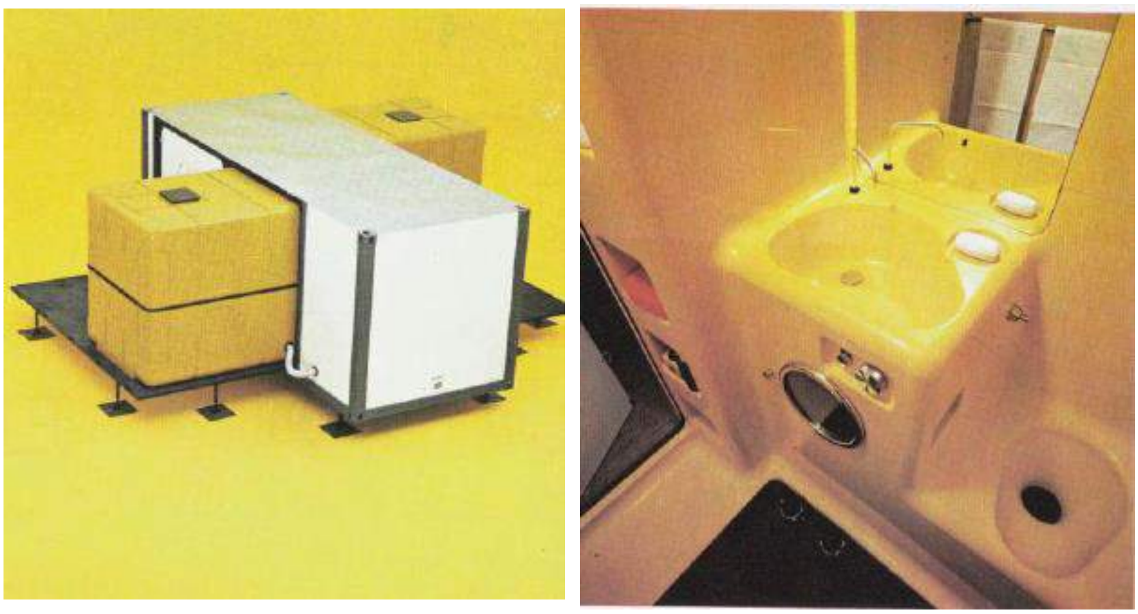

Figure 22 - Portable house inside a container by Marco Zanuso and Richard Sapper (Ambasz 1972).

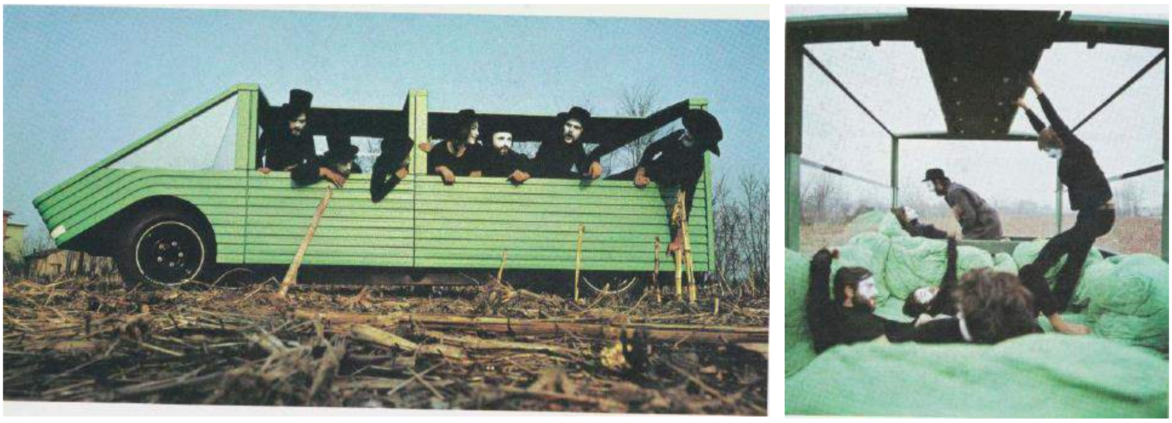

Figure 23 - Kar-a-Sutra, a mobile concept by Mario Bellini (Ambasz 1972).

Concepts of drawers and moving/flexible partitions are common as well as the merge of spaces - living + sleeping; eating + living; laundry + bathroom.

Examples of the book *Living in Motion* are also relevant because they represent a series of adaptable, collapsible, flexible and mobile furniture/house concepts. The concept of mobility, as Mathias Schwartz-Clauss mentions (Schwartz-Clauss and Vegesack 2002), recalls a nomadic society, a concept that can be transported to the present on Mars with the first flexible and mobile habitations.

Figure 24 - "Curtain Wall House" by Shigeru Ban (Schwartz-Clauss and Vegesack 2002).

The curtain walls of Shigeru Ban (Figure 24) can be transported into a colony on Mars to provide transformability of closed spaces into open spaces and vice versa. It allows the transition from the individual to the communal space.

 

Figure 25 - Left - "Wildbrook" by Urs Hartmann and Markus Wetzel (Schwartz-Clauss and Vegesack 2002); Right - "Naked House" by Shigeru Ban (Schwartz-Clauss and Vegesack 2002).

Also, the concept of compartments inside compartments (Figure 25) may be explored, where wheels can be of use to provide easy rearrangement of the interior space according to the inhabitants living preferences.

 

Figure 26 - "Schroder House" by Gerrit Rietveld (Schwartz-Clauss and Vegesack 2002).

The Schroder House (Figure 26) presents a dynamic configuration by adaptable walls and furniture. The walls move in sliding rails, resulting in a flexible and ample space for numerous functions, despite the small initial available area. Although the physical and psychological comfort of the settlers must be in mind, the concept of the Japanese capsules (Figure 27) may also be an inspiration for the space-saving arrangements of the interior space.

Figure 27 - “Nagakin Capsule Tower” by Kisho Kurokawa (Schwartz-Clauss and Vegesack 2002).

Another relevant design concept, although not focused on collapsibility nor flexibility is the concept presented by Thomas Missé. He designed a lightweight, stackable chair made from carbon fibre (Figure 28) that he believes will lower interplanetary importation costs (Missé 2018).

Figure 28 - Carbon fibre lightweight *Mars chair* by Thomas Missé (Missé 2018).

Bio design

Inspired by the bird bone, the Bone Armchair (Figure 29) is moulded from a mixture of marble and porcelain mixed with resin (Laarman 2018).

Figure 29 - The Bone Armchair inspired by bird bones by Joris Laarman (Laarman 2018).

In his book *Structure in Nature Is a Strategy for Design*, Peter Pearce studies geometry in Nature and inspires his designs in it (Figures 30 and 31).

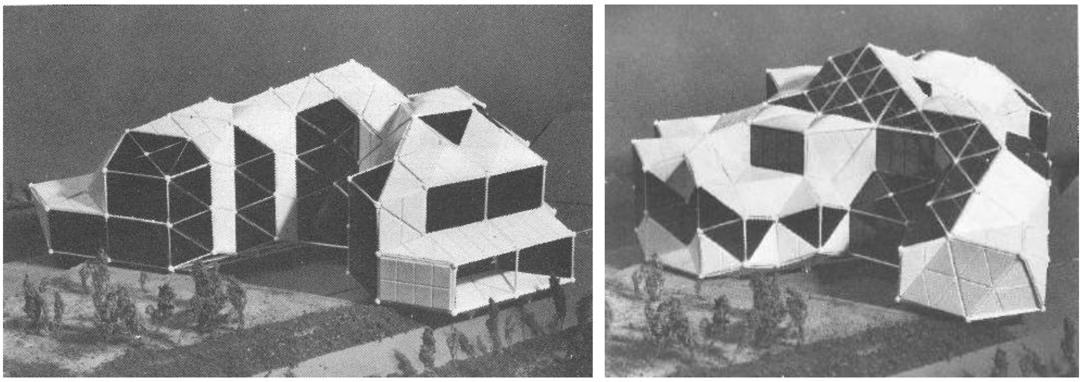

Figure 30 - Housing unit - north and south exposure by Peter Pearce (Pearce 1978).

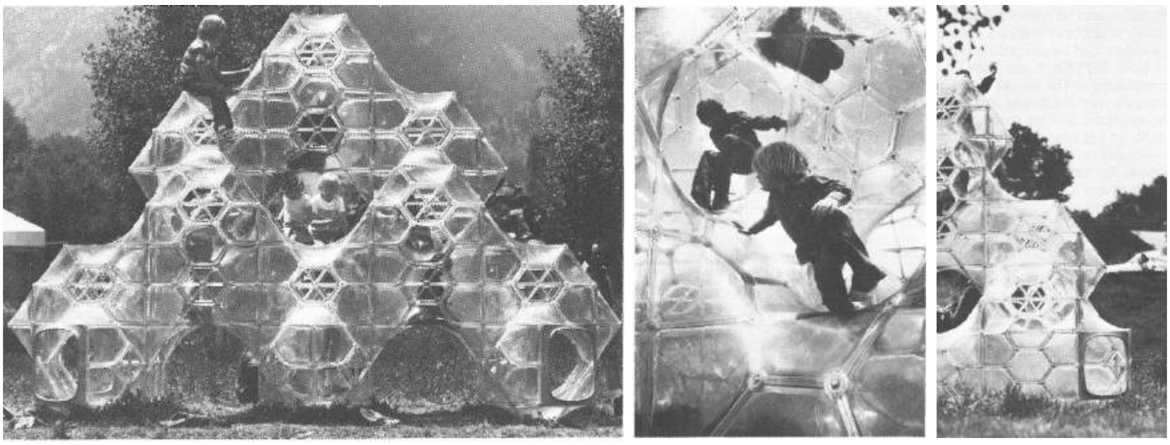

Figure 31 - Curved Space diamond labyrinth for a children park by Peter Pearce inspired by bubbles (Pearce 1978).

Structures

Archigram presented the Plug-In City (Figure 32) concept in 1964 and offered a new approach to urbanism, reversing traditional perceptions of infrastructure's role in the city. Though never built, their projects and ideas provoked debates, combining architecture, technology and society (Sadler 2005).

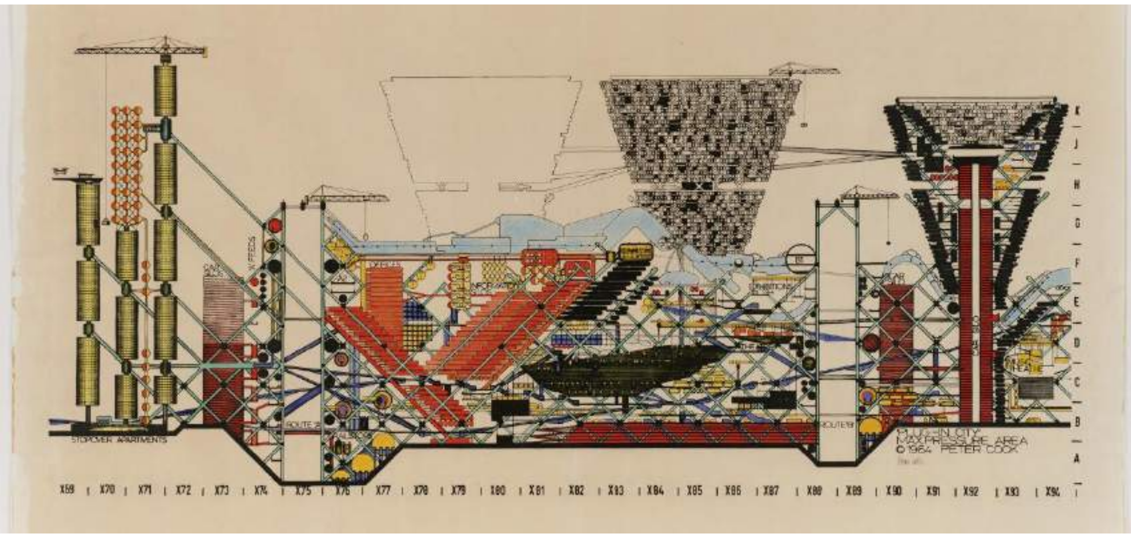

Figure 32 - "Plug-in city" by Peter Cook (Sadler 2005).

Modularity

Also in the book *Italy: the new domestic landscape* (Ambasz 1972) concepts of modules are presented. An example is the Ettore Sottsass's standardized structures of casings on casters (Figure 33). They could be aligned in big or small numbers, creating containers of diverse depths. Stoves, stools, toilets, showers, electronic entertainment systems, drawers or cabinets - could then be introduced inside.

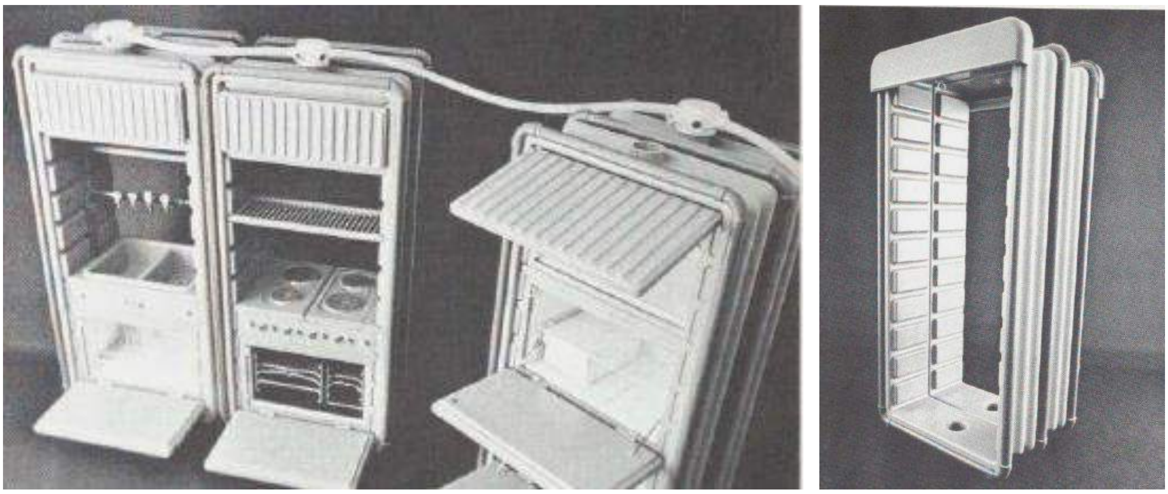

Figure 33 - "Equipped" container by Ettore Sottsass (Ambasz 1972).

3D printing

Additive manufacturing is a technique dating back to 1971 (Bowyer 2014) that consists in a computer controlled process of forming objects by sequentially adding and bonding material without any waste. It is exactly the opposite of subtractive manufacturing that removes material of an existing piece, which consequently generates considerable waste of material and energy. Also, by the subtractive method there are some tool restrictions that can prevent the creation of complex shapes, thus forcing complicated designs and assemblies (Mueller et al. 2018).

The additive manufacturing process is also known as three-dimensional (3D) printing. 3D printers use computer-created digital models to create real-world objects. To make the objects, the printers follow the shape of the digital model by stacking material layer upon layer. With this method, complex and hollow shapes become possible, which opens the door to design innovation. It is believed that 3D printing is the future of manufacturing and that it may revolutionize the way almost everything is done (Mueller et al. 2018). Barry Berman (Berman 2012) and other authors believe that it may lead to a new industrial revolution that could largely impact the manufacturing and building construction markets.

One of the most common methods is the fused deposition modelling (FDM). FDM is executed by using computer numerical control (CNC) to precisely force molten material through a die (extrusion) to specific places in layers. The molten material flows onto existing material and fuse together as the material freezes or solidifies (Berman 2012). This technique is primarily used to print thermoplastics such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) (Kading and Straub 2015), but other materials such as metal (Wang and Liu 2014) and other techniques for printing soft and interactive objects have recently been proposed (Hudson 2014). Methods using laser sintering, baked powders (Berman 2012), 3D printing of textile (Unver 2014) and larger models such as houses (Winsun 2017) have also been explored and proven to be feasible.

Within this context, it is important to understand the difference between the two sub-divisions of 3D Additive Manufacturing. The first is 3D Additive Fabrication, that refers to high precision printing (with minimum tolerances of

0,025mm) of relatively small objects (<1m^3) that are usually made of metallic or polymer materials. The second is 3D Additive Construction, the prime choice for the manufacturing process in this thesis. It refers to low precision printing (with 3 to 6mm of tolerance) of relatively large structures (>1m^3). Materials such as regolith or local resources from other planets can be used with this method. This allows the construction of structures at distant locations in our solar system - Moon, outer planets and their moons, Asteroids, and obviously, on Mars - without the need to transport the constructing materials from Earth. 3D Additive Construction[4] could provide the solution for extra-terrestrial shelter for humans and robots on planetary surfaces (Mueller et al. 2018) and therefore drastically reduce the manufacturing and shipment cost of these new homes (Kading and Straub 2015). However, by the time humans get to Mars, this manufacturing process will be much more developed by engineers, tolerances will reduce and precision will increase.

Examples of 3D printing on Earth show that many authors are already exploring different techniques to obtain numerous results. 3D printing with ceramics is a practice that is becoming common and the proof that a numerical based software can produce organic shapes with great precision (Figure 34).

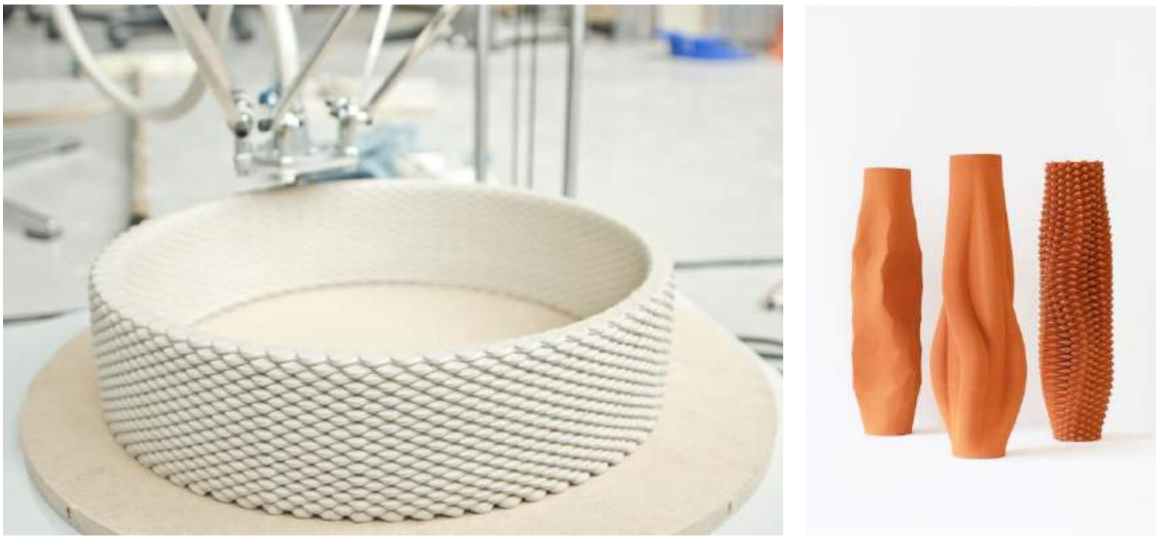

Figure 34 - 3D printing with ceramics by Olivier van Herpt (Herpt 2018).

[4] Which is currently under development in many places including the NASA Kennedy Space Center "Swamp Works" innovation labs (Mueller et al. 2018).

Following the personal computer and a range of digital advances, the advent of the personal fabricator (Figure 35) has provoked a revival of the idea of "making your own things." (Unfold 2018).

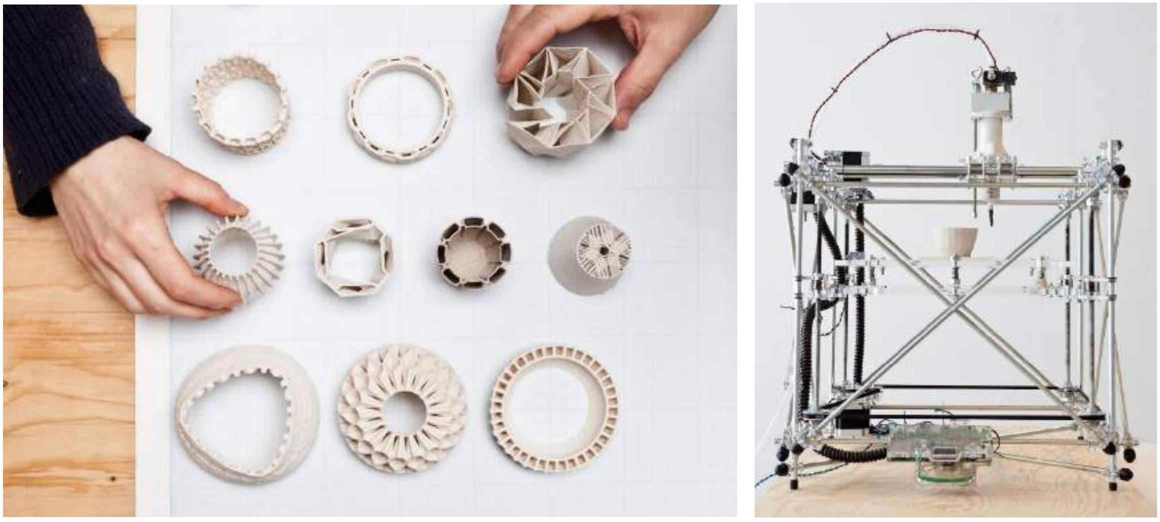

Figure 35 - 3D printing with ceramic by Unfold (Unfold 2018).

Project Milestone is a project that intends to 3D print habitable concrete homes in the Eindhoven neighbourhood of Meerhoven (Figure 36). The ambitious plan is to print five homes in the same area, making this the first time that a community of homes are being 3D printed (Watkin 2018).

Figure 36 - Eindhoven's an Entire Community of 3D Printed Homes (Watkin 2018).

The Grip robot by the Institute for Advanced Architecture of California attaches itself to the printed structure by clamping it between 4 rollers (Figure 37). The nozzle can dynamically be moved sideways to have higher control over the printed shape. Heaters are used to increase the speed of material curing time.

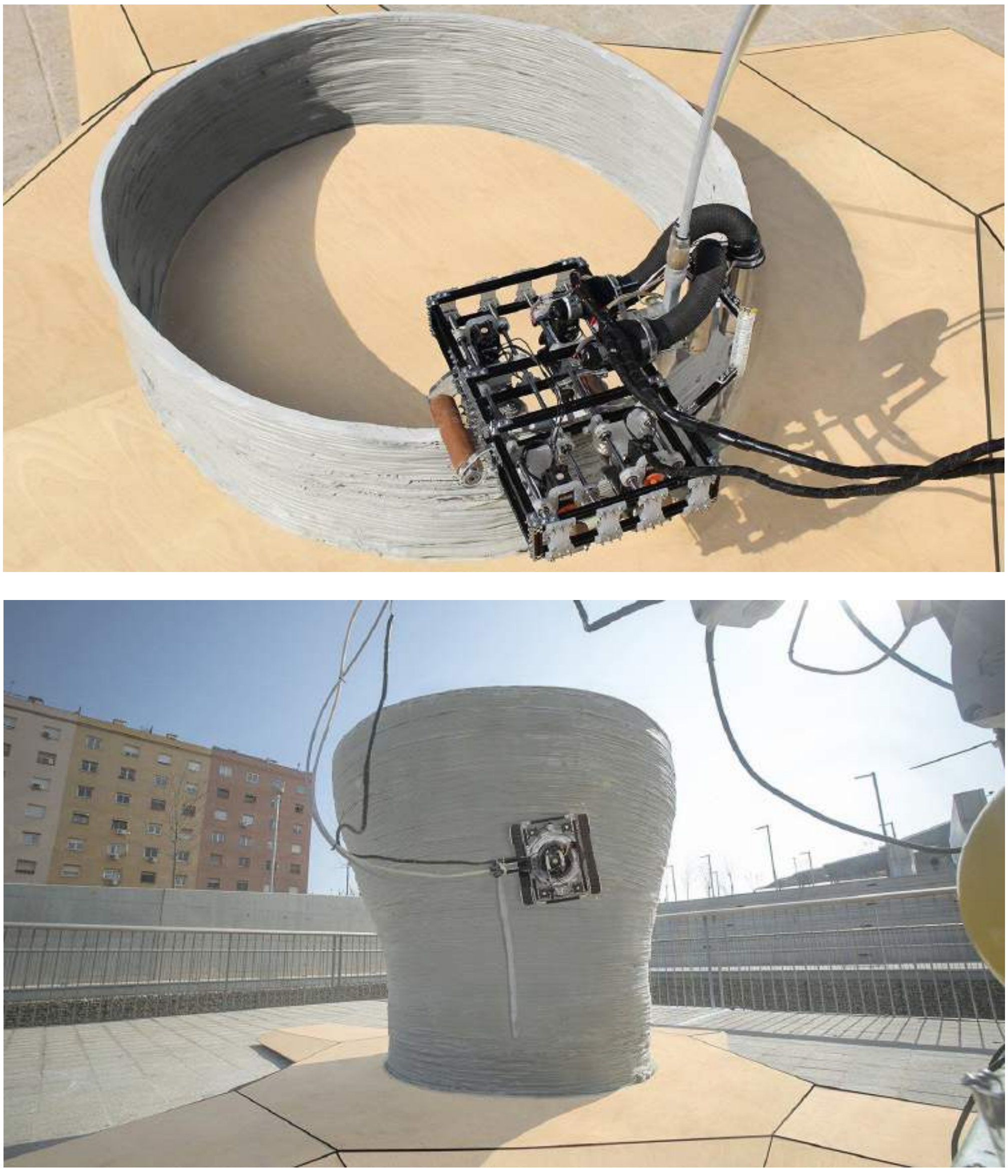

Figure 37 - Small Robots printing big Structures. “Monkey robot” (Iaac 2018).

3D printing with basalt

Besides the suggestion of many authors, such as Cesaretti (Cesaretti et al. 2014), Benvenuti, Ceccanti and De Kestelier (Benvenuti, Ceccanti, and De Kestelier 2013), of 3D printing with lunar or Martian regolith, some authors have proposed 3D printing with basalt. Benjamin Kading and Jeremy Straub provide in their article (Kading and Straub 2015) explanations and images of a proposition of a specific basalt 3D printer (Figure 38).

As McSween, Taylor and Wyatt note (McSween, Taylor, and Wyatt 2009), Mars is very well suited to the use of Basalt 3D printing because it has a higher concentration of basalt when compared to the other “rocky” planets in the solar system. The abundance of this material reduces transportation costs and the use of 3D printing for structures is also advantageous because the printed structures become ready for use almost immediately after they are completed. Since the melting point of basalt is not that high, it can be used in the FDM printing method. Basalt also has a comparatively low permeability constant, so it appears feasible to use it to contain the atmosphere if combined with pressurization techniques (Kading and Straub 2015).

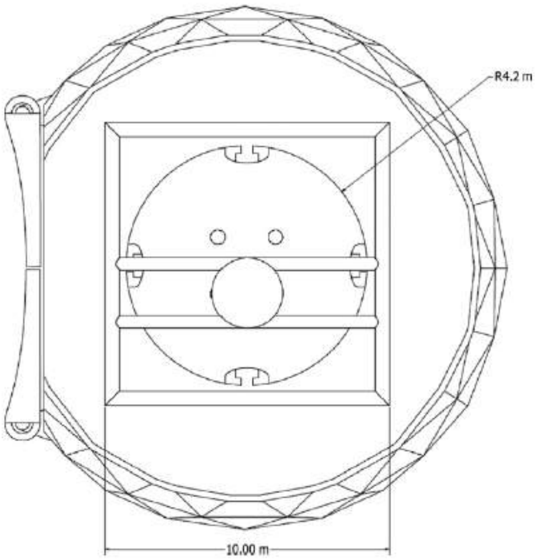

Figure 38 - Proposition of a larger dome with smaller dome and a basalt 3D printer inside (Kading and Straub 2015).

Methods of transferring regolith to a 3D print head mounted on a robotic arm are being developed at KSC to investigate the feasibility of adhering the regolith particles together in successive 2D layers to achieve a 3D printing proof-of-concept (Figure 39) process based on additive manufacturing.

Figure 39 - NASA’s experimentation on basalt 3D printing (Mueller et al. 2018).

The results have been promising to date, but only at a bench top scale, however additional work is still ongoing. Future experimental work aims to improve the consistency of material properties throughout the build and scale up the process to create larger structures in the order of several metres in height (Mueller et al. 2018).

Materials

Many uses for basalt have been proposed by the company Vulkan-Europe B. V.[5]:

- Basalt fibre
    - Concrete, civil engineering, man-made underground structures, sea bars and facilities, architectural forms, decorative elements, etc.
- Basalt fibre roving (basalt fibre winded on bobbins)
    - Tapes, mats, cords, ropes, nets, etc.
- Basalt fibre rebars (with resin)
- Needle-punching material (non-woven fabric)
- Basalt woven textile
- 3D printing with basalt regolith fines

Basalt fibre

"Basalt fibre can be considered as a new commodity, although its origin is already billions of years old." - Hans de Wit[6]

Fibre made from basalt is a 100% natural product drawn from the lava of melted basalt cobbles with a temperature of 1500°C. No other ingredients are applied to the lava. Using the extrusion method, the lava is pushed through holes that are thinner than a human hair. The main difference between basalt stone and basalt fibre is that by this extrusion technique the basalt is not capable to harden with a crystal structure, therefore it becomes an amorphous structure.

This gives the fibres great properties since it is 2,5 times stronger than steel and 4 times lighter than steel; it has no conductivity and no corrosion; its

[5] Vulkan-Europe B.V. is an organization whose mission it is to distribute basalt fiber products to companies in Europe that can use basalt fiber as a material for their products (V. 2018c).
[6] Retrieved from an e-mail exchanged with Hans de Wit, the CEO of the company Vulkan-Europe B. V.

production takes only 40% of CO_2 when compared to the production of steel; the availability is immense, considering that about 30% of the Earth's crust is basalt; it does not require deep mining and has the possibility of being recycled. These properties remain still between the temperature range of -200°C to 800°C (retrieved from a document sent by Vulkan-Europe B.V. company - complete information document in Appendix II). Further properties and specifications of basalt fibre can be found in Table 2 and Table 3.

Properties of basalt fibre	
Impact	Significantly increases the impact strength
Fatigue	Significantly increases the fatigue strength
Tensile strength	Significantly increases the tensile strength
Tear	Significantly increases the tear strength
Mechanical stress	Increases resistance to mechanical stress
Shrinkage	Significantly reduces shrinkage deformation
Abrasion	Increases resistance to abrasion
Crack resistance	Increases crack resistance
Plastic deformation	Eliminates the appearance of plastic deformation
Water/frost resistance	Increases water and frost resistance
Fire resistance	Has absolute incombustibility (-260°C to 750°C)
Durability	It is a durable material
Environment impact	Chemically pure (basalt fibre = 100% stone)
Environment resistance	Resistant to aggressive environments

Table 2 - Properties of basalt fibre. Adapted from a document sent by Vulkan-Europe B.V. (complete information document in Appendix II).

Specifications of basalt fibre	
Cut length of chopped fibre	3mm, 6mm, 12mm, 18mm... ($\pm$1,5)
Diameter of the fibre	12 microns ($\pm$1,5)
Humidity	>0,3%
Modulus of elasticity	Minimum of 75GPa
Coefficient of thermal conductivity	0,79 mm - 0,038 W/MK

Table 3 - Specifications of basalt fibre. Adapted from a document sent by Vulkan-Europe B.V. (complete information document in Appendix II).

Due to its unique physical, chemical and mechanical properties, basalt fibres can be used in extreme conditions, where other materials cannot or require periodic maintenance or replacement. It is particularly effective on the reinforcement of concrete for use in regions of high seismic instability; near the ocean where constant erosion leads to surface abrasion; hydraulics structures and roads, bridges and asphalt, where high resistance to penetration of salts is required.

Technical tape is obtained from the weaving of the basalt fibre bobbin (Figure 40). This tape can be used in a wide range of temperatures and aggressive environments as a load-bearing element, as a reinforcing element, as sealing of static joints of machines and mechanisms, etc. Adding epoxy resins to the fibres, it is possible to make rebars (Figure 40) and mats for the reinforcement of concrete (retrieved from a document sent by Vulkan-Europe B.V. company - complete information document in Appendix II).

Figure 40 - Top left - BFRP reinforcement for concrete constructions (District 2018c); Top right - Chopped fibre for concrete mixture (District 2018c); Medium left - Non-woven basalt fabric (District 2018c); Bottom left - Cord made from basalt fibres (V. 2018a); Bottom right - Continuous basalt fibre winded in a bobbin (V. 2018b).

Non-woven basalt fabric

The non-woven fabric (Figure 40) is a needle punching material developed by the company Vulkan-Europe B. V. It is made out of chopped basalt fibre (60 - 100mm) and bound by the needle-punching method without the use of any binding agents. It can also be covered with foil on one or two sides.

The application temperature of this material ranges between -260°C and 800°C, being that it maintains its structural strength within this range. It is used for vibration and acoustic insulating. It is also extremely lightweight, elastic and fireproof (additional characteristics in Table 4).

Some possible uses for this fabric are the manufacturing of filters, composites, thermal-insulating and soundproofing materials. It is also highly suitable as a fire protection material in high-rise buildings, industrial projects and fire-hazardous constructions (i.e. factories for the petrochemical industry). This material is available in rolls of 1m or 1,5m wide and up to 20m long. It has 6mm or 10mm of thickness (V. 2018d).

Material Properties

Sensorial		Technical	
Glossiness	Satin	Fire resistance	Good
Translucence	0%	UV resistance	Good
Structure	Open	Weather resistance	Good
Texture	Medium	Scratch resistance	Poor
Hardness	Resilient	Weight	Light
Temperature	Warm	Chemical resistance	Good
Acoustics	Good	Renewable	No
Odour	None		

Table 4 - Non-woven basalt fabric properties. Adapted from “Non-woven Basalt Fabric” (District 2018c).

Basalt woven textile

The basalt woven textile (Figure 41) is another material developed by Vulkan-Europe B. V. made of 100% natural basalt stone. The high modulus of elasticity of this material results in an exceptional tensile strength, more than twice the tensile strength of steel. It has high corrosive and chemical resistance and works well in salt solutions, acid solutions and particularly alkali liquids.

Figure 41 - Basalt woven textile sample provided by the company Vulkan-Europe B. V. Photographs by the author.

The fibres that compose this basalt fabric are 2,5 times stronger than steel and 1,5 times stronger than glass fibre. When combining heat-insulating items made from basalt fibre with inorganic binding agents the material may be used up to 700˚C. Moreover there is a range of compositions consisting of basalt rocks that have a thermal stability of up to 800˚C. Another characteristic of the basalt fibres is high electric-insulating and transparency for electromagnetic radiation (additional characteristics in Table 5). This allows basalt fibres to be used for the production of electric insulating materials for low-voltage (up to 250V) and high-voltage (500V) equipment (District 2018b) (more photographs of the sample sent from the company and more information on Appendix III).

Material Properties

Sensorial		Technical	
Glossiness	Satin	Fire resistance	Good
Translucence	0%	UV resistance	Good
Structure	Closed	Weather resistance	Good
Texture	Smooth	Scratch resistance	Good
Hardness	Soft	Weight	Light
Temperature	Warm	Chemical resistance	Good
Acoustics	Moderate	Renewable	No
Odour	None		

Table 5 - Basalt woven textile properties. Adapted from "Basalt Woven Textile" (District 2018b).

Basalt knitted fabric

"From a stone to a fibre – this is really a fascinating progress." - Gülsüm Görgülü[7]

In the context of a diploma work from a student of textile engineering at Swisstulle Ltd.[8], the company developed knitted fabrics made of basalt fibres (Figure 42).

[7] Retrieved from an e-mail exchanged with Gülsüm Görgülü, the Customer Service and Purchasing Technical Textiles representative of the company Swisstulle Ltd.

[8] For more than 35 years, Swisstulle Ltd. is an important participant in the technical textiles market. It produces knitted fabrics, as well as it is a specialist in various finishing processes (Swisstulle 2017a).

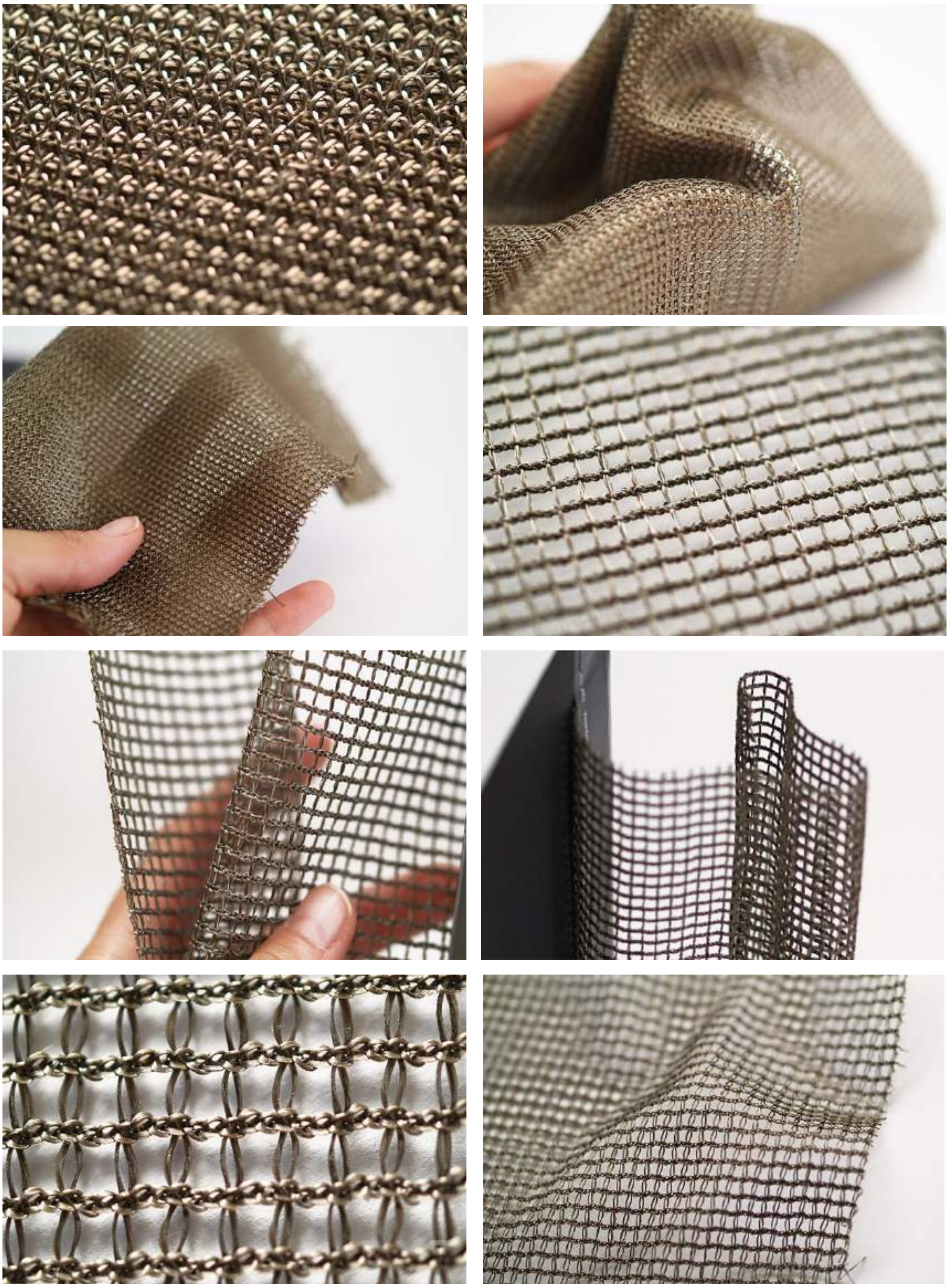

Figure 42 - Basalt knitted fabric samples provided by the company Swisstulle Ltd. Photographs by the author.

These high heat basalt knitted fabrics are made from stone fibres that are obtained from the volcanic basalt. This material is available in three different knits, does not break or fall apart, is fireproof[9] and is 100% basalt (Swisstulle 2017b). The strength and elongation of basalt fibres is 15% higher than glass fibres and its melting point is at 1450˚C. It has low thermal conductivity and high electrical resistance (additional characteristics in Table 6). This material has a good drapability and it can be used for fire protection, isolation, carrier tapes and, for example, as reinforcement fabric in the maritime branch. Basalt prevents algal growth and is more durable under water (District 2018a). These basalt qualities are not standardly in our range (more photographs of the samples sent from the company and more information on Appendix IV).

Material Properties

Sensorial		Technical	
Glossiness	Glossy	Fire resistance	Good
Translucence	0-50%	UV resistance	Good
Structure	Open	Weather resistance	Good
Texture	Variable	Scratch resistance	Good
Hardness	Soft	Weight	Light
Temperature	Cool	Chemical resistance	Good
Acoustics	Poor	Renewable	No
Odour	None		

Table 6 - Basalt knitted fabric properties. Adapted from "Basalt Knitted Fabric" (District 2018a).

[9] A1 incombustible according to DIN 4102 (Swisstulle 2017b).

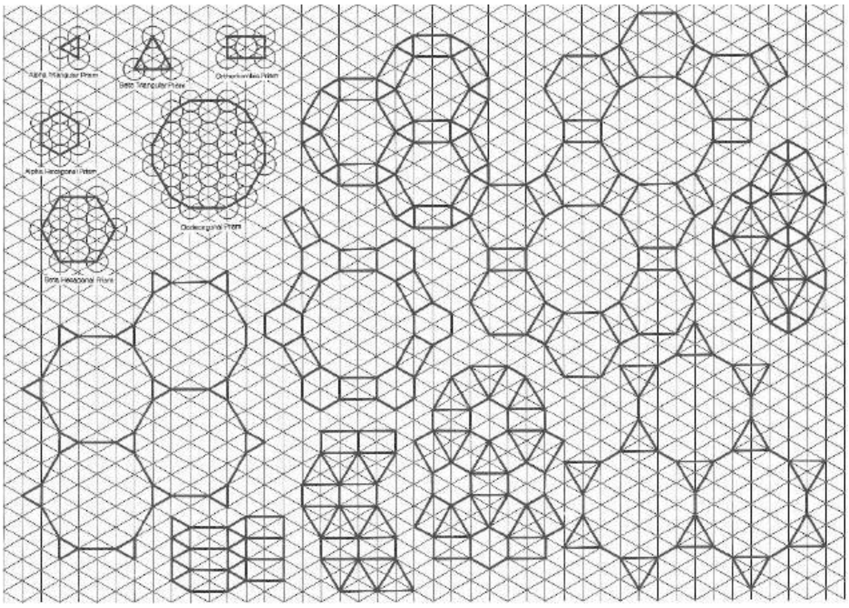

Figure 43 - Study of pack arrangements of hexagons combined
with triangles, squares and dodecagons by Peter Pearce (Pearce 1978).

Design process

Figure 44 - Mind map method on the theme *Exploration and colonization of Mars*.

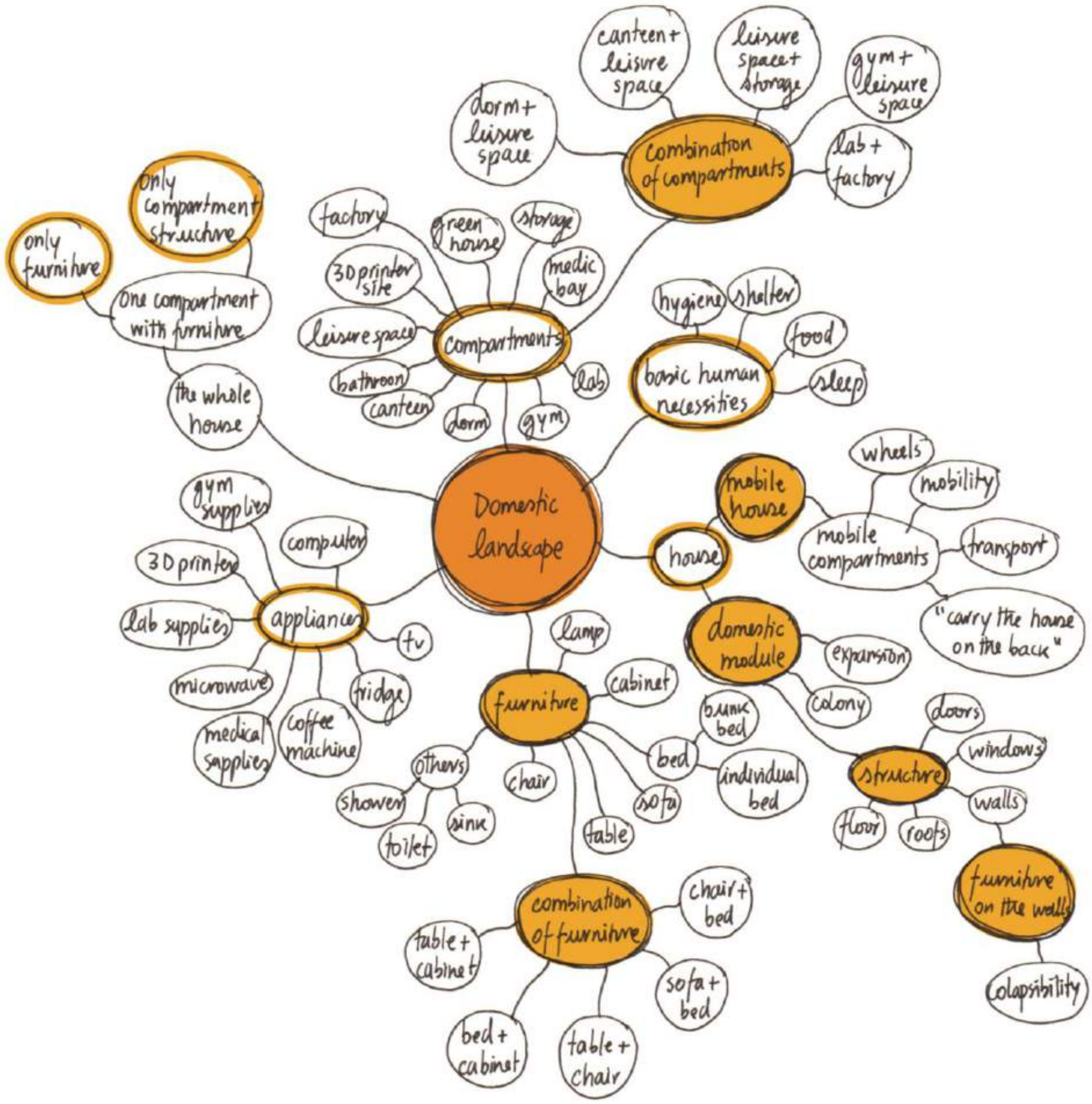

Figure 45 - Mind map method on the theme *Domestic landscape*.

The design process for this project, as mentioned in chapter one, started by following the methodology of the Delft Design Guide techniques (Boeijen and Daalhuizen 2010). After reading the book, a set of design techniques and methods, were considered appropriate for this thesis, selected and followed. In order to create a design goal the methods *Collage Techniques*, *The ZEN Design Method*, *Trends Analysis*, *WWWWWH*, *Problem Definition*, *Checklist for Generating requirements, Design Specification (Criteria)* and *Process Tree* were selected and executed in the correspondent order. For the creation of product ideas and concepts the method *The Brainstorming Method* and *Mind Map* were selected and executed.

Figure 46 - *Collage* of a compilation of images retrieved from TV series and movies for the application of the method *Collage Techniques* of the Delft Design Guide (Boeijen and Daalhuizen 2010).

The aim of the *Collage Method* was the determination of criteria (design requirements) and a visual analysis (Figure 46) of the context, target group, environment, usage, colours, materials and textures of the design program. The outcome was a table of derived criteria and a direction for idea generation.

The ZEN Design Method was used to reach an abstract level. Instead of thinking of designing a house the idea was to think of a way to live. It allowed the focus to be on quality and the user's rituals that are involved in the acts of domestic living on Mars. The outcome was a diagram that comprised the desirable qualities of material and social interactions (Figure 47) and a direction for innovation on product design.

With the *Trend Analysis* method it was possible to identify the target group needs and future trends. The outcome was several trend pyramids (Figure 47) based on the PESTED approach (Political, Economical, Social, Technological, Ecological and Demographical) and organized by levels: microtrend - product level (1 year), miditrend - market level (1-5 years), maxitrend - consumer level (5-10 years) and megatrend - societal level (10-30 years). Interesting directions for new product ideas were also a result.

The goal of the *WWWWWH* method was a problem analysis and draft of a first design brief. It is based on the answers of the questions: Who? What? Where? When? Why? and How? The outcome was a drafted design brief and a diagram of answers organized around the main problem.

When utilizing the *Problem Definition* method a more structured description of the design problem was the objective. The definition of the problem was a result of the answers to the questions: What is the problem? Who has the problem? What are the goals? What are the side-effects to be avoided? and Which actions are admissible? The outcome was a hierarchy of the problem divided into smaller ones and an explicit final statement on the problem: *The main problem is the construction of structures with 3D printing technology using in-situ resources that will guarantee the colonization and exploration of Mars.*

Both *Checklist for generating requirements* and *Design Specification (Criteria)* methods were useful to determine an extended list of requirements and standards divided by seven categories: Origin, Production, Distribution, Installation, Use, Maintenance and Disposal.

The *Process Tree* method was used to make a visual diagram that summarizes the design requirements determined by the previous methods. Its goal was an overview of the important processes that a product goes through: origination > manufacturing > assembly > distribution > installation > operation > maintenance > use > reuse > disposal.

Finally, the *Brainstorming and Mind Map* methods were used to explore product ideas and design concepts. The outcome was structured thoughts and ideas about the problem and a graphical representation around two central themes: Exploration and colonization of Mars (Figure 44) and Domestic landscape (Figure 45).

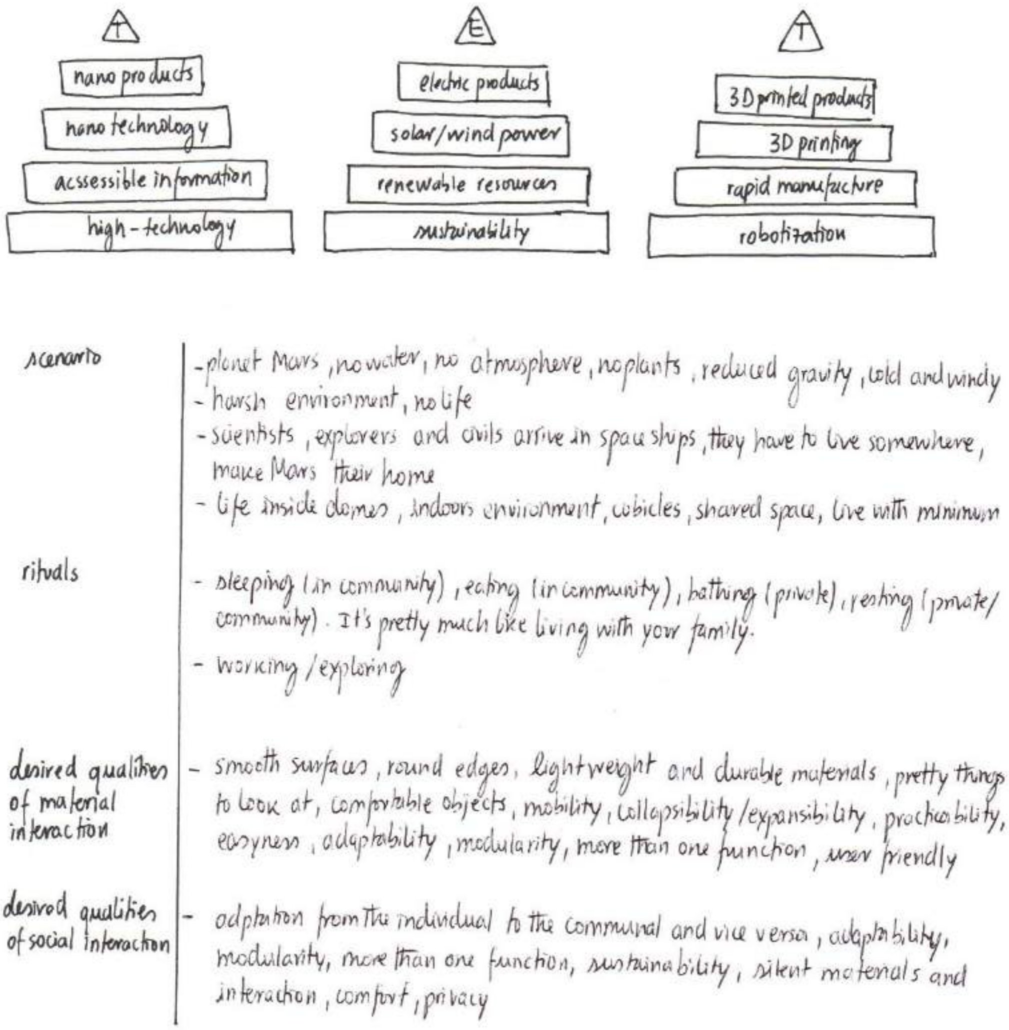

Figure 47 - Top - Trend pyramids of *Trend Analysis* method; Bottom - Diagram of scenario, rituals involved and desirable material and social qualities of *The ZEN Design Method*. Both for application of the Delft Design Guide (Boeijen and Daalhuizen 2010).

Factors to consider when designing for planet Mars

Designing for outer space and specifically for planet Mars is not the same thing as designing for planet Earth. Designers must reckon with the constant lethality of the external environment of Mars, the enormous costs of transporting materials, life support systems, limited opportunities for rescue and resupply and the psychology of isolated, artificial and confined environments. Design solutions that work well on Earth may be too expensive or fail in space. However they are still designing for human beings and therefore some considerations have to be attended. Although the planet, gravity, and manufacture process change, the anatomy of the human being does not change, or at 'least not so soon'. Men walks on a vertical axis and lives in an orthogonal way. They are fragile and do not resist the environment without shelter. Just like on Earth, design for space must cope with volumetric limitations, activities, layouts, adjacencies, customization, doors, windows and straight walls, ceilings and floors (Harrison 2009).

As seen in chapter 2, there are some differences and similarities between Earth and Mars that require close analysis in order to understand which essential factors have to be considered when designing for the Red Planet (Figure 48). From the analysis four categories of requirements were identified: shelter requirements that include a set of crucial elements to be considered for human protection against the environment and life support; design requirements that focus on how the shelter should be designed and organized as well as the well-being and comfort of the settlers; technological requirements that concerns on how the shelter could be built; and human requirements, which in turn fall into three categories - biological requirements for safety and good physical health, psychological requirements for high performance and good mental health, and sociocultural requirements for positive interpersonal and intergroup relationships.

	problems	requirements	
enviroment	**temperature**	heated spaces	shelter living space
	atmosphere	vacuum block	
	radiation	radiation block	
	meteorites	meteorites protection	
	gravity	pressurized suits	
	pressure	pressurized environments	
	distance	use of *in-situ* resources reduction of costs	
	oxygen	oxygen production	life support
	water	water extraction/production	
	energy	energy production/storage	
	food	food production	
	plants	plants grown in labs	
	life	human/animal colonization	
	materials	synthesis of bioplastics and others	material supply technology
	manufacture	easy manufacture/assemble mass production	

Figure 48 - Summarized analysis of identified problems of planet Mars and respective essential requirements to be considered for the design process.

Shelter requirements

To protect themselves from the harsh environment of Mars, humans will certainly need to build a shelter. The average temperature on the surface of this planet is -63°C which means that humans will require temperature-controlled dwellings and heated spaces to live in. Mars has quite a weak atmosphere when compared to Earth, so humans will also have to be protected against the nearly vacuum from the exterior and the possibility of small meteorites colliding with the surface of the planet. Also due to the lack of a dense atmosphere and magnetic shielding, high levels of cosmic radiation can target the human body. Protection against the radiation is crucial because long-term exposure to galactic cosmic rays (GCR) and particles released in sudden solar particle events (SPE) can result in cancer and death (Reitz, Berger, and Matthiae 2012). According to Sheshpari, Fuji and Tani 2-4m of overburden rock can stop its penetration (Sheshpari, Fujii, and Tani 2017). The gravity on Mars is approximately a third of what humans re used to at home, meaning that they will need pressurizes spacesuits and pressurized environments to live in.

For now, the Red Planet appears to be an inhospitable place that has very little amounts of oxygen and water and apparently has no life. Humans require life support elements such as breathable air, food, water and other resources in order to survive. They will have to produce oxygen, reclaim water from waste, produce it or extract it from the ground or air, produce energy and store it with solar panels and other sustainable methods, grow plant on laboratories in order to produce oxygen and food and bring animals and humans to colonize the planet and eventually terraform it.

Design requirements

living space

- **adaptability**
- **modularity**
- **recycling**
- **light**
- **colors**
- **textures**
- **well-being**
- **comfort**
- **conectivity**
- **hobbies**
- **mate**
- **private vs communal**

design

Figure 49 – Summarized dissection of the essence of the domestic life and respective requirements to be considered when designing for the living space.

In the past, when humans started venturing into the sea to seek new worlds their departure was into a tangible unknown because even though no one had been there before they knew what they were going to find – water, land, plants, animals, human beings and cultures. This time, adventurers will departure to an intangible unknown scenario because it is an even more remote, unexplored and different place that apparently has a mixed sense of emptiness. These two ways of colonization are very distinct. In the second, humans will have to build a complete new way of living in a new artificial horizon. At the same time it will give a new freedom and the possibility to work in a total new dimension of space living. A new social, spatial ideological dimension anchored in new utopias that will come through in wildest dreams.

As presented above in the Design program subchapter, the goal is to design a dwelling that occupies as minimum space as possible taking into account the physical and psychological comfort and well-being of its inhabitants (Figure 49). Is has to adapt to the environment and to the place where it will be deployed but it also has to adapt to its inhabitants and to their different individual and communal activities and personal preferences. At the same time the dwelling must be sufficiently fixed to provide private space for the individual (single person) or the collective (family). The modularity compartment approach can easily adapt and change the environment as well as it allows the possibility for further expansion of the colony with the addition of more modules. The colour of the walls and floorings should be as neutral as possible in order to be accepted by all cultures and ethnic groups. The design of the dwelling and its interior objects should fit the natural environment and the colours of Mars, however, the settlers should be allowed to personalize the space with their own personal preferences. The materiality of things, the materials and their textures also need to be considered for the settler's well-being as design requirements.

Settlers should have spaces with sufficient interior volume to work efficiently and live comfortably and also a fair distribution of areas for different activities. Work areas should be separated from resting places. Bigger areas should exist to allow the inhabitants to hang out together and perform a range of communal activities but also smaller areas are important for the privacy on the individual or small groups of individuals. The design of the colony should offer ample areas with appropriate lighting for the task, facilities and objects that are easy to maintain and repair *on-site* and clear channels for accurate communication. Sustainability is also very important and the goal must be to create a self-sufficient dwelling that recycles everything[10].

[10] Recycling everything, even the sweat (Braungart and McDonough 2002).

Technological requirements

Obviously, there are still a lot of technological barriers to overcome until the first humans can set foot on Mars. The design concept, that will be presented further, represents a vision that is a structure of analysis that shelters technologies in ascension, optimism and a good dose of dreams and madness. However, it relies on engineering and technical advancement in several areas such as basalt additive manufacturing; 3D printers; and technology and analysis of the produced basalt structures' strength and permeability, ability to maintain a pressurized and heated environment, radiation blocking properties and protection against meteorites, sustainability, comfort and well-being.

Since Earth and Mars have a considerable amount of distance separating them and it is too expensive to send materials for construction on spaceships, the use of *in-situ* resources is a clear requisite. Materials should be extracted from the Martian landscape and processed *on-site* and without the need of factories or big complex machinery. Apart from the resources, the manufacturing process should also be simplified in order to allow the settlers, with the help of robots and printers, to easily build a colony within a short amount of time. Standardization and mass production is preferred but the process should allow adaptability to the place where the shelter will be implemented.

Biological requirements

Mars is a lethal and unforgiving environment, so a major concern is the protection of the life and mental stability of the people who venture there. Threats to safety come from structural and mechanical problems, communication failures, insufficient or wasted supplies, among many others (Harrison 2009).

This demands designs that can resist to the harsh environment of space, and that are user-friendly and tolerant to people's limits and mistakes. They must also seek life support systems that provide reliability and comfort for settlers. Challenges comprise the achievement of proper temperature and humidity balance, effective cosmic radiation shielding, the maintenance of a continuous supply of fresh air and water, the development of multicultural meals, and improved hygienic systems that are easy to use and perform well. Quality sleep is important for people to do their jobs properly therefore sleeping compartments may require better shielding from sound, light, and adjacent activities (Harrison 2009). Design can also help here with the distribution of activities inside the colony by making sleeping compartments far away from the compartments that produce more noise.

An infirmary is essential to the colony to mitigate the effects of illness and cure cuts, broken bones, burns, and other injuries. This facility will also have to be equipped with diagnostic and surgery tools, and, eventually, the ability to synthesize drugs and fabricate prosthetic devices. Settlers will have to deal with pregnancies, births and post natal care, gingivitis, cataracts, hearing loss and many other problems as well as handling the end of life for those who are terminally ill (Harrison 2009).

Psychological requirements

A broad view of human factors is essential to protect settlers from an accumulation of stress that could lead to performance lapses, interpersonal conflicts, and possible psychiatric breakdowns.

Issues regarding the human-system interface such as techniques for presenting information in clear way, switches and knobs that are quickly identified and easy to use, activity stations that grant people to work comfortably, will have to be considered. Besides this there are many design issues with the humans and intelligent machines partnership[11]. Basic rules such as simplicity of design and operation, high reliability, ease of repair, room for improvisation, and other features that reduce the probability of misuse or error should be applied. Psychologists, architects and designers should work together to assure good behavioural health and the presence of high levels of personal adjustment, affectionate interpersonal relations, and positive interactions with the physical and social environments by designing colonies that are occupant centred and activity oriented (Harrison 2009).

Leisure time is very important for the sanity and entertainment of the settlers. Both individual and communal activities such as personal hobbies, reading,

[11] Artificial intelligence, automation, and robotics for agricultural production, mining and manufacturing.

watching television, listening to music, looking outside windows and exercising should be guaranteed in order to transform this inhospitable place into a pleasant and desirable home. The presence of plants and green spaces is also an important for the mental health of the settlers. In the International Space Station many astronauts post photos of trees on the walls (NASA 2018c). There should be an effort of surrounding spacefarers with actual plants, first inside the domestic environment and later outside the dwelling, to allow them to feel the nature they're used to at their home planet. Another important issue is the monotony of colours. People need to feel a variety of textures and colours but Mars has a similar-tone colour pallet that visually is very appealing but may become tiring. Compartments should be neutral colour but the inhabitants should be able to personalize and customize their personal space with colours, fabrics and other things.

Sociocultural requirements

Space adventurers will be cut off from their usual social contacts and confined within a relatively small group of other people. Isolation and confinement are always considered major challenges of living in space (Harrison 2009). Contact with people from mission control on Earth is reducing and autonomy of outer space crews is increasing, which will raise even more as distances from Earth and communications delay increase. Teams must be effective and interact successfully with other teams.

To avoid interpersonal tensions, designers should consider various mechanisms for minimizing social clashes. Inhabitants will want small areas for personal conversations or two-person interactions, but also large rooms for conversation, activities and parties. One of the big challenges for space architects and designers is the creation of environments that support privacy but discourage people from isolating themselves from the others. In addition, cultural differences also increase design challenges. Language, personal hygiene standards, social interaction distances and idiosyncratic preferences for food and entertainment can lead to conflicts. Designs that avoid ethnocentric biases and recognize cultural differences will be preferred. At some point, settlers will need similar social institutions to the ones that support societies on Earth - a government, an economy, an educational system, a legal system, and if not organized religion then something that provides a coherent world-view and a set of values that provide for spiritual needs. Another issue for settlers will be dating, mating, and procreating in a confined environment. Designers need to be sensitive to the varied types of families that will go to Mars and others that might evolve there. The proper privacy and special care must be provided.

After a few years, Martian inhabitants are likely to develop a new culture which reflects their adopted environment, living conditions, and interactions with one another. The Martian culture may become increasingly differentiated from Terrestrial culture. Designers can provide elements that help carry forth terrestrial culture, but also give settlers ways to strengthen their emerging culture on Mars. Habitats should provide enough flexibility to adjust to different crew sizes, tasks, equipment and supplies (Harrison 2009).

Design program

In 1972 the architect and industrial designer Emilio Ambasz was invited by The Museum of Modern Art in New York to organize an exhibition in order to understand how the Italian designers and architects were responding to the new paradigms of modern domestic life. The selected participants were challenged to design a domestic environment adaptable enough for different activities, private or communal, but also sufficiently fixed for the individual privacy (Ambasz 1972).

The concerns of the design program of the early seventies, towards the design of the domestic landscape, prevail and are perfectly valid today with the new design program of the twenty-first century's greatest endeavour – the Red Planet exploration and future settlement. They even share some of the requisites, for instance modularity, adaptability, mass production and, among others, reduced costs.

Beyond this, as seen in the literature review and in the previous subchapter, creating a settlement for humans on another planet naturally demands additional requirements and special cares. The goal is to design a dwelling that occupies a lava tube in the most space-saving way, taking into account the physical comfort and psychological well-being of its inhabitants. If it is designed from to inside to the outside then the overall piece will be able to be adaptable to any environment (Munari 1999) or lava tube. This strategy contributes for a reduction in costs and reduction of resources to the minimal. Furthermore the manufacture must be intended for mass production and it should be easy to assemble, not requiring the use of big complex machines. The growing 3D printing technology can be used for this purpose. Also, the material choice has to be carefully thought through. Since cargo will have to be transported from Earth to Mars in a rocket's restricted space and of limited weight, it will not be possible to transport all the materials we need to build things on Mars so it is extremely important to explore *in-situ* resources such as basalt and use them as primary resources for 3D printing and construction. Sustainability is also very important, so the dwelling must recycle everything and achieve self-sufficiency. Big numbers of people should be sent to Mars in order to prevail and make the colonization worthwhile.

Regarding the interior of the habitats, as Ambasz describes in his design program for the new domestic landscape (Ambasz 1972), the domestic environment on Mars "must also be designed with the possibility of being adaptable to the different individual and communal activities, but at the same time be sufficiently fixed to provide a private space for the individual." The design of modular blocks allow easy adaptation to the environment as well as the possibility for further expansion of the colony by the addition of more blocks. The colour of these blocks should be as neutral as possible with a design that fits the natural environment and the colours of Mars. Green spaces are also very important and even if it will not be possible to have gardens outside the dwelling plants should live inside the domestic environment.

"...the dwelling should be adapted more and more to man,
rather than the other way around." - Joe Colombo
in the book *Italy: the new domestic landscape* (Ambasz 1972).

Shape Definition

After the initial brainstorming phase and definition of design program and requirements, a shape study started. The search for the optimal shape for the module and for the colony was inspired by the book *Structure in Nature Is a Strategy for Design*. There are innumerable examples in nature of form and structure that are generated from the combinations of different physical and chemical components (Pearce 1978). Peter Pearce studies the presence of geometry in Nature (Figure 50) and inspires his designs in it.

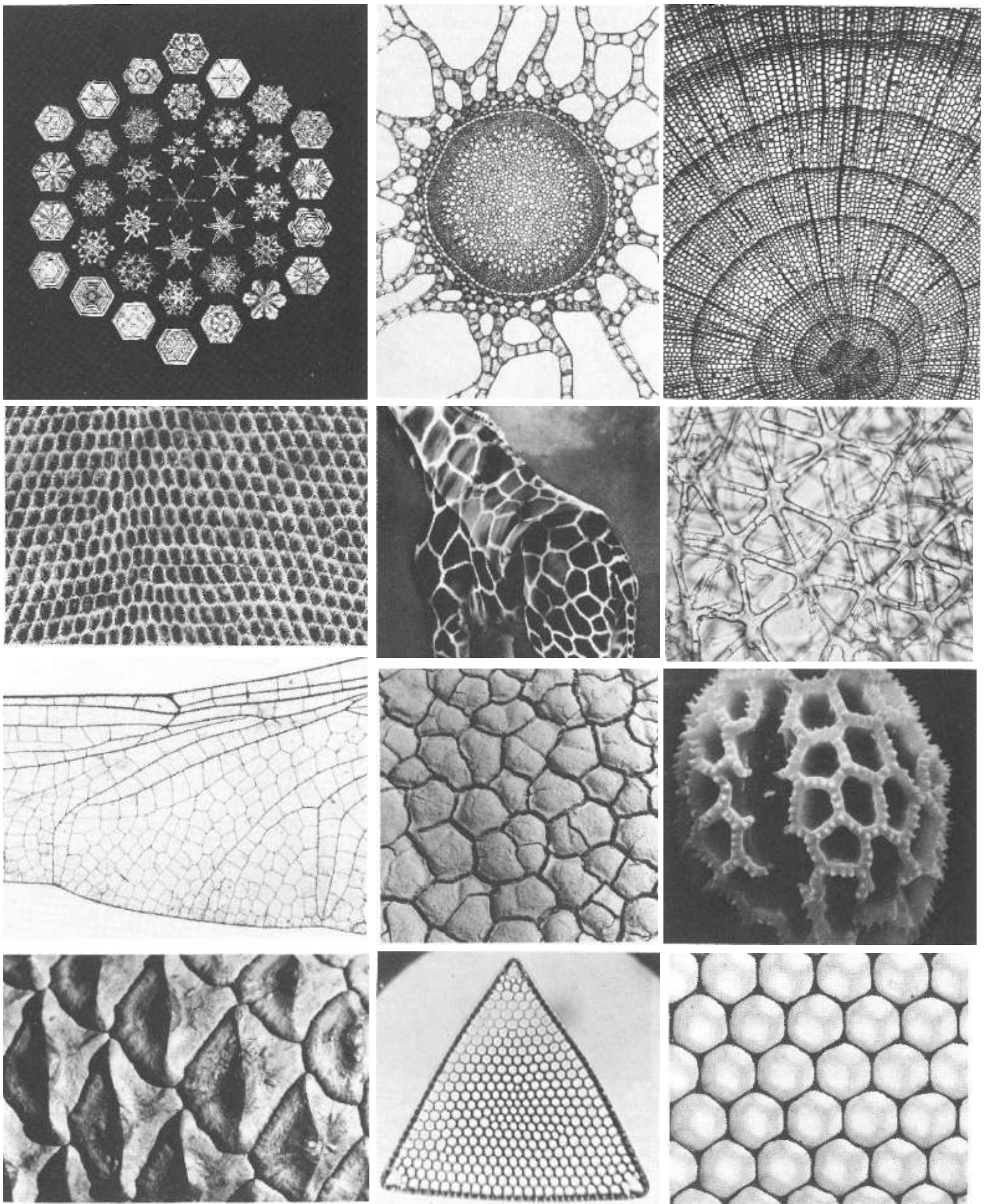

Figure 50 - Compilation of hexagons and triangles found in nature. Images retrieved from the book *Structure in Nature Is a Strategy for Design* by Peter Pearce (Pearce 1978).

The principle of closest packing is equivalent to the principal of triangulation, and it is well known that triangulated frameworks exhibit inherent geometric stability. These principals operate independently of scales or materials, with the same energetically conservative effect. Its inherent stability always establishes a condition of minimum potential energy whether at the molecular level, the cellular level, or at the man-made structural level (Pearce 1978).

The project presented in this chapter was also inspired by Nature and, in order to understand which shape would work best in a close packing, a series of geometrical shape studies were conducted starting from the circle, and then increasing the number of vertices until the dodecagon (Figure 51). The goal was a conclusion about the prime shape to use in the design of the individual module.

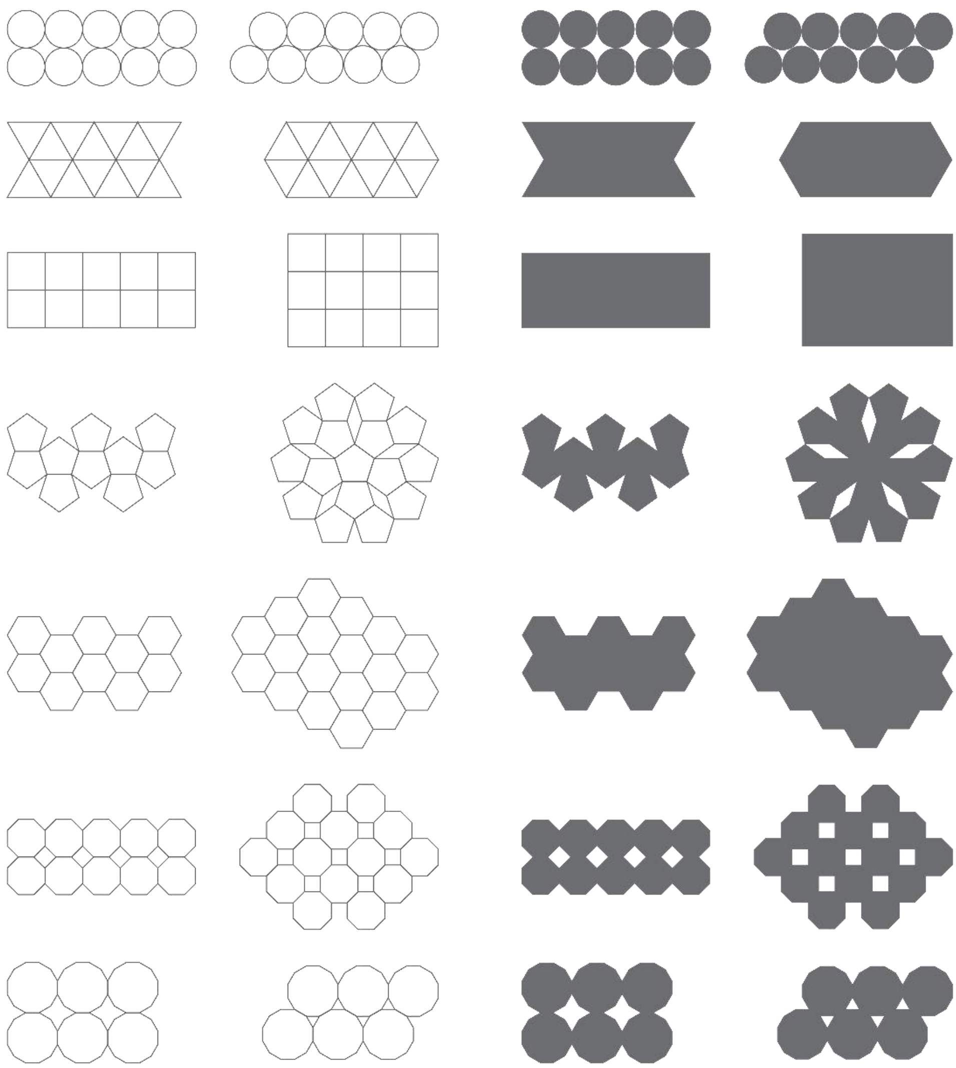

Figure 51 - Study of the best shape for a close packing.

As it can be seen in Figure 50, the triangle, the square, the rectangle and the hexagon are the polygonal shapes with the least amount of waste of space when organized in a close pack. However, since the design program comprises an individual module to function as a room for settlers to live in, the triangle is automatically eliminated because of its closed interior angles. It limits the domestic life and hinders the disposition of furniture. In terms of angles, the square and the rectangle are quite the opposite because the majority of commercialized furniture design follows strait lines and right angles. The square and the rectangle are the most preferred shapes in Earth's architecture, but on an irregular lava tube on Mars it becomes more important a shape like the hexagon that, when joined together in a close pack, can have a more organic configuration to fit the available space in the most economical way. Also, the hexagon has a good weight distribution.

The hexagon is clearly the optimal polygonal shape and therefore the chosen one for the prime geometry for the individual module design. As seen in the beginning of the subchapter (Figure 50), the hexagon is present in many plants, animals and other elements. Perhaps the most familiar example of closest packing in Nature, is the honeycomb of the bee (Figure 52). This system of regular hexagons contains the greatest amount of honey with the least amount of beeswax and is the structure which requires the least energy for the bees to construct (Pearce 1978).

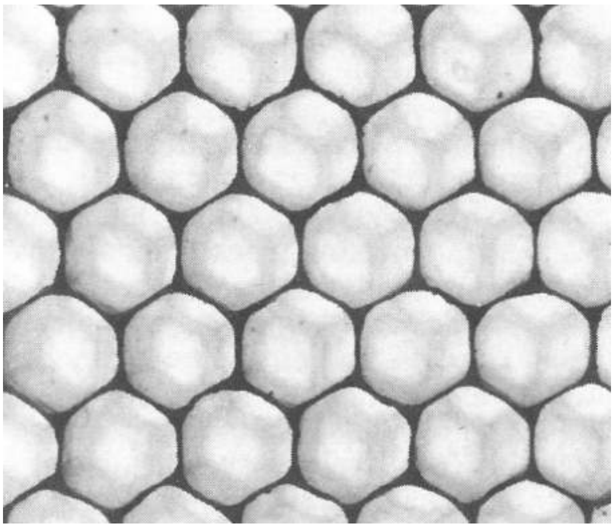

Figure 52 - Honeycomb of the bee (Pearce 1978).

The repeated or iterated pattern of triangles is related to the closest packing and is a pervasive geometrical arrangement in the physical world. If circles are packed as densely as possible and their centres are joined, triangles are formed (Figure 53). When the centres of packed hexagons are joined, a group of triangles also form (Pearce 1978).

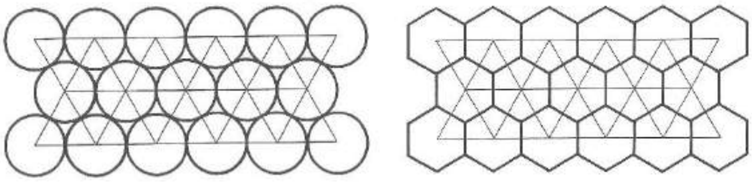

Figure 53 - Closest packing of circles and hexagon with triangulation (Pearce 1978).

Considering the partitioning formed by the closest packed circles, although the circle is very economical shape because it encloses maximum area for its given perimeter, small concave triangles are formed between the circles. These concave triangles match the least area with the greatest circumference. Consequently it can be said that, considering the entire plane, circle packing is not the most economical system. However, let us allow the circles to change their shape in order to fill up the concave triangles, forming hexagons (Figure 54). This becomes the most economical method for partitioning a surface into equal units of area. This demonstration suggests that hexagonal cells match minimum structure to maximum usable area (Pearce 1978).

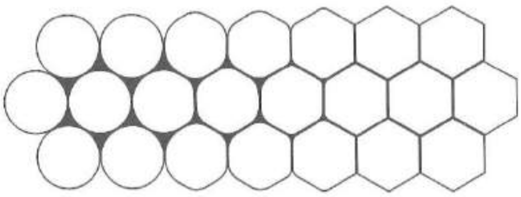

Figure 54 - Closest packed circles changing into closest packed hexagons (Pearce 1978).

Apart from the presence of polygons in nature the design proposal (shown further in this chapter) also attended to their presence in science fiction movies and TV shows and space design. The octagon, probably the shape that appears more frequently, is commonly seen in corridors and windows (Figures 55 and 56). The reason for this is because the ideal shape for a pressurized compartment in a spaceship is a cylinder, so they use octagons to approximate the shape of the circle. However, as concluded in this subchapter, the octagon is not the best shape for a close packing. The triangle is often used for dome construction (Figure 57) and the hexagon is present mainly in windows, corridors, domes and also in many other patterns (Figures 58 and 59).

Figure 55 - Octagonal-shaped corridor. Image retrieved from the movie *2001: A Space Odyssey* (Kubrick 1968).

Figure 56 - Octagonal-shaped windows. Image retrieved from the TV series *The Expanse* (Fergus and Ostby 2015).

Figure 57 - Triangulated dome. Image retrieved from the movie *The Martian* (Scott 2015).

Figure 58 - Hexagonal-shaped window. Image retrieved from the TV series *Mars* (Bormanis, Fisher, and Janszen 2016).

Figure 59 - Hexagonal-patterned window glass. Image retrieved from the TV series *Lost in Space* (Allen, Sazama, and Sharpless 2018).

Alveolar structure

Since the deployment of the colony will be inside a lava tube, humans will be protected against the exterior environment and especially against the radiation and meteorites. Despite that, the wall of the tube in itself is neither enough to guarantee sealing against the cold nor from the nearly vacuum environment. It becomes necessary the use of man-made walls with pressurized spaces in order to protect settlers against the exterior. Another issue is the lightness of the 3D printed structures because without big machinery it will not be possible to carry too much heavy things.

The best way to design the colony's walls, and turn them into light structures, is the addition of air. In Nature, some of the mostly used light, strong and economical internal structures are the bubble structure, the corrugated cardboard structure, the alveoli structure and the hexacomb structure (this last one was already applied in the shape definition presented above). In the manufacturing industry and design these structures are also used for economic reasons, lightness properties and strength abilities. A good example is the alveolar polycarbonate (Figure 60). It is manufactured by extrusion which makes it a simple and economical technological process. Because of its high levels of flexural strength and torsion resistance it is frequently used in ceilings and covers, even allowing curvatures that are not easily obtained with, for example, glass.

Inspired by this product, the design of the walls of the module combine the use of septum (Figure 60) and alveolus (Figure 60). These structures will reduce the quantity of printed material to a minimum without any loss of strength and turn them into lighter walls.

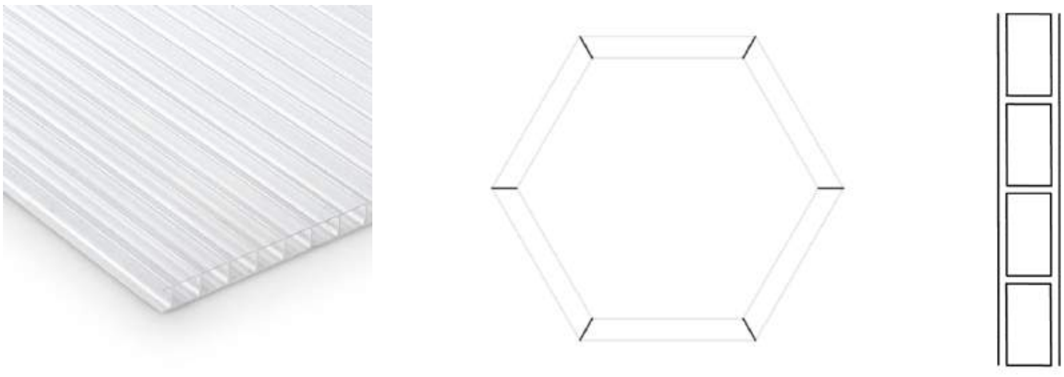

Figure 60 - Left - Sheet of alveolar polycarbonate; Middle - Use of septum in the hexagons vertices; Right - Possible configuration for 3D printed alveoli.

Individual module proposal

Even though 3D printing technology allows the design of the module and the colony to be completely organic, a human being lives in an orthogonal way, which requires that the walls, ceilings and floors are straight. With that said, the hexagonal prism was the chosen form for the basic module (Figure 61).

According to what was exposed in the previous subchapter, the use of an alveolar structure results in a maximum resistance to a minimum material consumption. As the final design has cells enclosed in alveoli, the module will exhibit high resistance both to flexion and to torsion even with thin walls. By introducing alveolus, the stresses to which the modular structure will be subjugated will be distributed over the perimeter surfaces of the alveolus. In this proposal there will also be extrusion of an alveolar structure, but this time the extrusion will be by addition of material. Applying air to the walls, ceilings and floors will then ensure sealing from the exterior making all the interior protected.

Considering an interior area of $9m^2$ as an acceptable living space minimum for a human being on Earth, this design proposal for Mars presents a living space minimum interior area of $18m^2$. As it can be seen in Figure 61, the interior of the module has 4m from wall to wall which takes into account the wellbeing of the Martian citizen and gives him enough comfortable space to live and work. An acceptable interior height on Earth is 2,5m so for Mars the same dimension[12] was used. To guarantee protection against the outside the walls were projected with 30cm of width and the alveoli with approximately 45cm of length and 30cm of width. The floors and ceilings do not require such width so they were designed with 20cm of height and an alveolus filling with approximately 27cm of width. The proposed material thickness for the 3D printing of the entire module is 3cm.

[12] All the proposed measurements on this paragraph were a result of a conversation with the civil engineer specialized in structures António Soares. Eventually it has to be considered that the evolution of the Martian Men might require adjustments in the height of the modules.

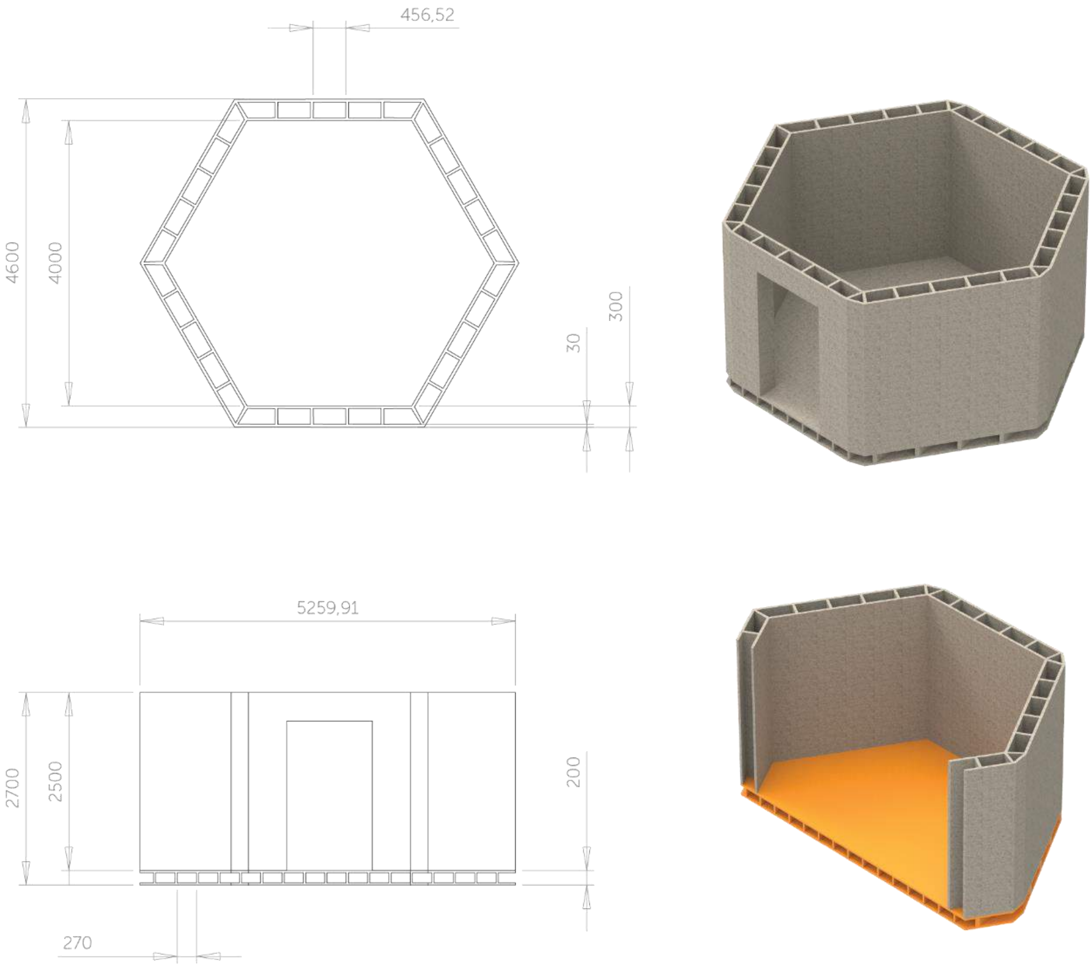

Figure 61 - Technical drawings and modulation of the individual module with section view of the alveolus in the bottom right[13].

The main advantage of modularity, as seen before, is the possibility of infinite arrangements and the flexibility to rearrange modules whenever necessary. This allows the deployment of a colony on any lava tube on Mars because the design of the basic module and the arrangement of many of these modules permits the creation of organic configurations that can adapt accordingly. Just like the bee adapts its hive to a tree and a spider adapts its web to a plant.

If a module has a problem, it could be sealed off while the other modules would still be habitable.

[13] The orange color in the section view was merely used for visual purposes.

Colony proposal

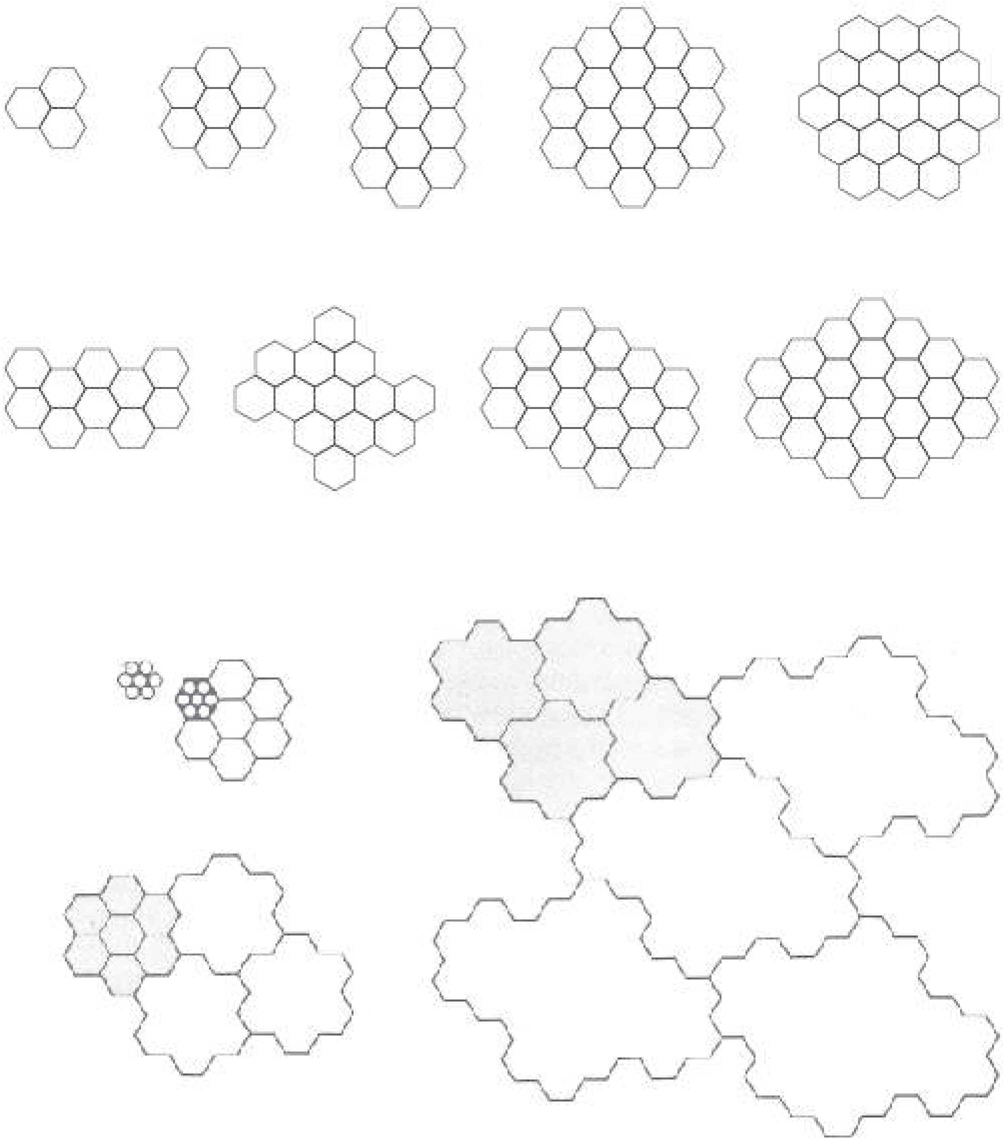

Figure 62 - Top two rows - Examples of different studied pack arrangements of hexagons. Bottom row - The hexagonal cell as an intrinsic determination of the larger form (Pearce 1978).

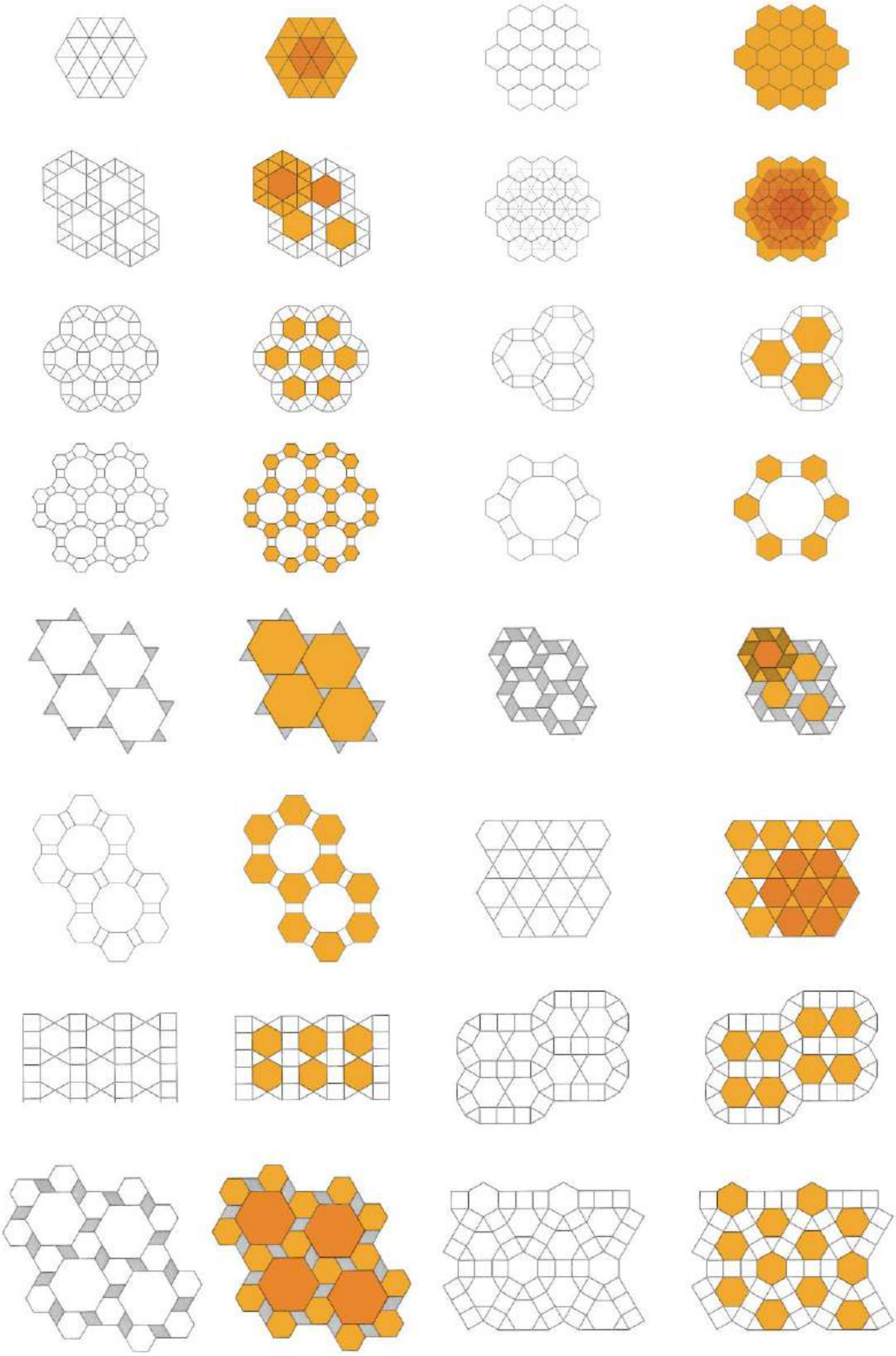

Figure 63 - Examples of different studied pack arrangements of hexagons combined with triangles, squares and dodecagons. Adapted from "Structure in Nature Is a Strategy for Design" (Pearce 1978).

With the basic hexagonal module defined, the next step comprised the arrangement of multiple modules and the search for a colony configuration that would allow maximum use of available space inside the lava tube. The hexagon was already proven to be an economical shape that allows organic configurations when joined together in a close pack. With that said, the direction for the initial configuration study was the arrangement of hexagons in different types of packs (Figure 62).

After a while it became clear that corridors were necessary in order to transit between compartments and allow bigger spaces to fit more people and communal activities. The addition of other regular polygons to the hexagon pack allow another type of configuration called the tessellation of the plane. A regular tessellation is a pattern of congruent regular polygons filling the whole plane, on which all vertices of the tessellation are surrounded alike (Pearce 1978). Some examples of regular and semi-regular tessellations of the plane are shown in Figure 63 with the hexagonal shape highlighted in orange.

For the design of the colony it was considered a lava tube[14] with 25 metres of width, 10 metres of height and 40 metres of length.

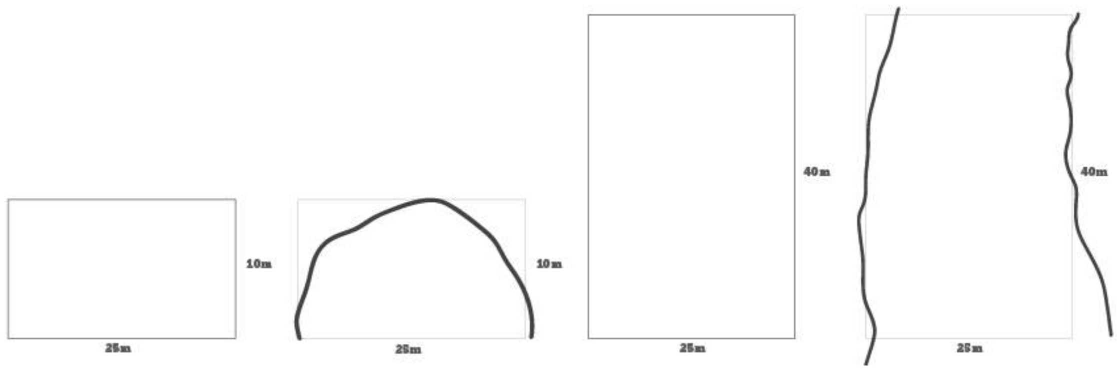

Figure 64 - Drawing by hand of a section of an imaginary lava tube, respecting the dimensions of the rectangle.

[14] Since there are no images on Martian lava tubes yet, the drawing of the presented lava tube is fictional and it only serves as a starting point for the final drawing of the colony proposal. The attributed measures were based in a research on Pico island’s lava tubes in Azores, Portugal. The biggest tubes there have around 8-10m of height, 10m of width and are more than 100m long. As the volcanoes of Mars are the largest in the solar system it was considered reasonable to use a lava tube sample of approximately 10m of height, 20m of width and 25m of length (they can be much larger but this way it is presented a believable hypothesis).

With the shape of the lava tube defined, some of the shapes of Figure 63 were combined to obtain colony configurations inside this particular lava tube. Three hypothesis of possible colony configurations are presented in Figure 65. The first hypothesis explored the basic hexagon module arranged in a closest pack. The use of only hexagons gives an acceptable organic shape to utilize most of the lava tube available space. However, when hexagons are combined with rectangles a bigger dodecagon space results and even more space of the lava tube is utilized. The third, and chosen, hypothesis achieves the ultimate utilization of available space by adding irregular shapes (highlighted in orange) that follow the walls of the tube creating some sort of second *skin*.

The area that results from the merge of dodecagons with the irregular shapes that follow the tube's wall can be utilized for storage, corridors, small bathrooms, among others.

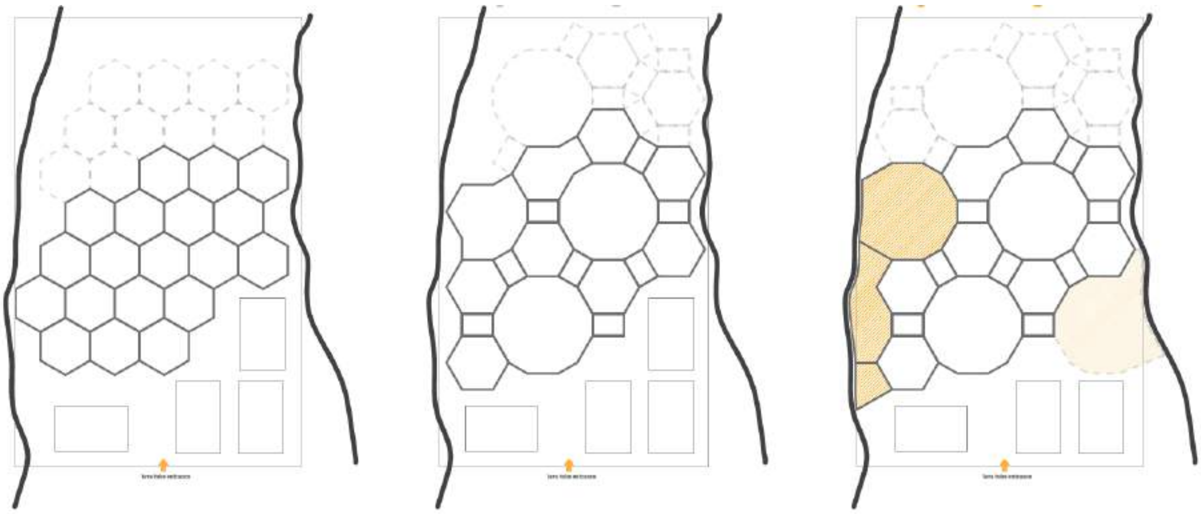

Figure 65 - Right - Optimal colony shape for the utilization of maximum space available inside the lava tube.

The merge of hexagons and rectangles create new shapes for alternative spaces and activities requiring bigger configurations. A hypothesis of a possible distribution of compartment functions is presented in Figure 66.

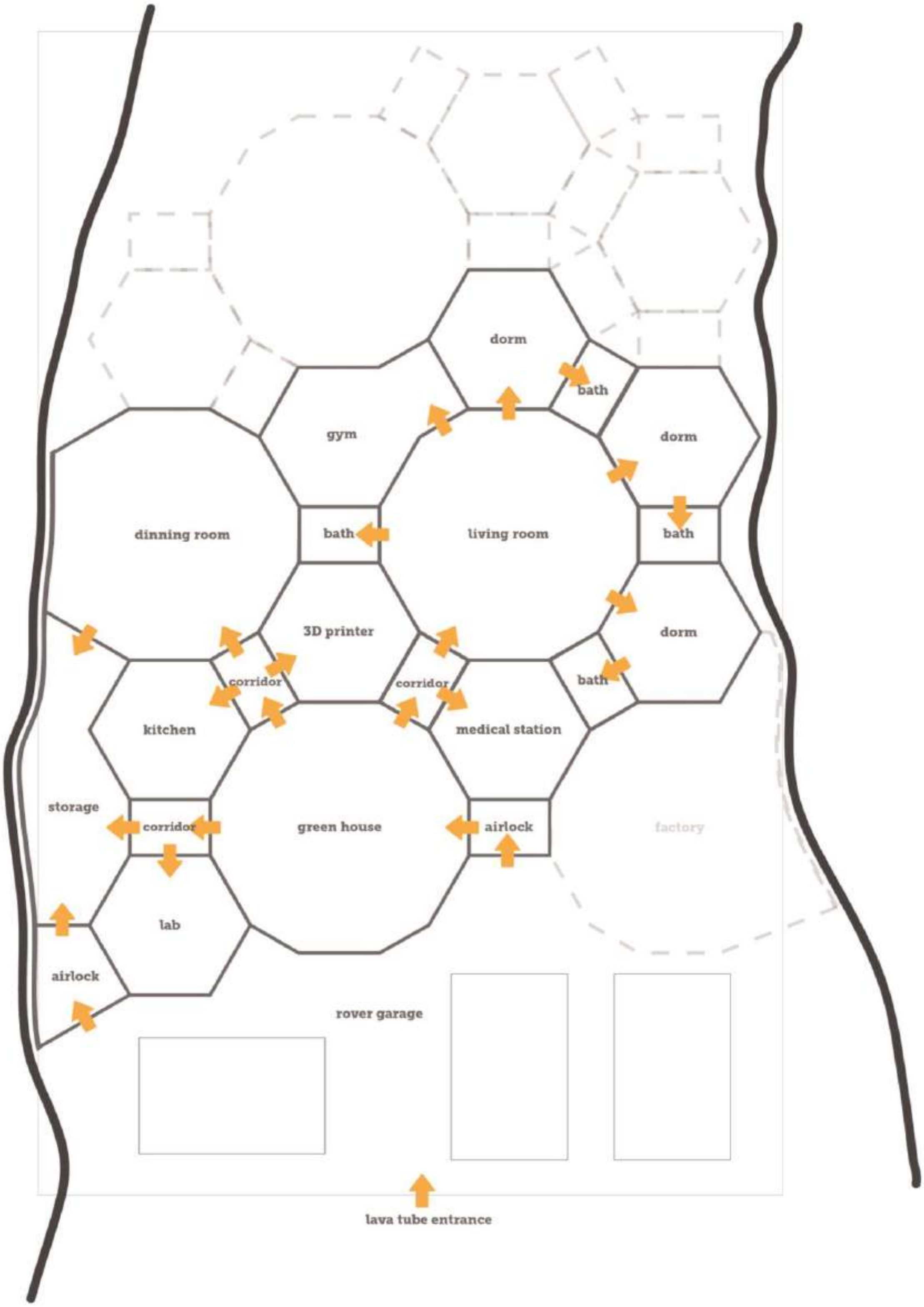

Figure 66 - Possible function distribution of the colony by compartments and their respective passages highlighted in orange.

In the design process a reflection on basic and essential rituals and ceremonies of the twenty-four hours of a normal day, and the correspondent essential compartments to support it, was made (Figure 45). When placing the functions within the chosen colony (Figure 66), the main concerns were the separation of the noisy compartments from the resting compartments and the use of the dodecagons for communal living spaces. The presented distribution of spaces is, again, only a possible hypothesis. The dorms can have one bed or multiple bed bunks, depending on the number of settlers living inside the lava tube. Each dorm has a bathroom inside and the resting area has been allocated deeper inside the tunnel for better protection. The bigger spaces are attributed with living room and dining room functions and surrounding them, a kitchen, a lab, a 3D printer site, a medical station and a gym. The dining room is inside the irregular-shaped room close to the tube's wall. The greenhouse was placed close to the entrance of the lava tube in order to have easy access from the exterior. Airlocks were placed on the entrances of the colony for pressurization and depressurization purposes. Also, the rectangles seen in the entrance of the colony are a representation of robotic rovers that are parked on the edge of the lava tube; the dashed lines represent possible future expansion of the colony; and the orange arrows represent the passages between the compartments. Because this colony is designed to be built inside a lava tube, alternatives for windows will have to be found. An example could be the use of screens displaying a live view of the surface of Mars or even images of plants or other preferred views.

The overall length of the proposed colony is approximately 24m and the overall width is 23m, which results in a living space area of 358m^2 (Figure 67). The dodecagon room has 17m from wall to wall and an interior area of 45m^2. The rectangular corridors have 2,2m of length, 1,4m of width and an interior area of 3m^2. The hexagon, as stated above, has 4m from wall to wall and an interior area of 18m^2. The height of all modules is 2,5m.

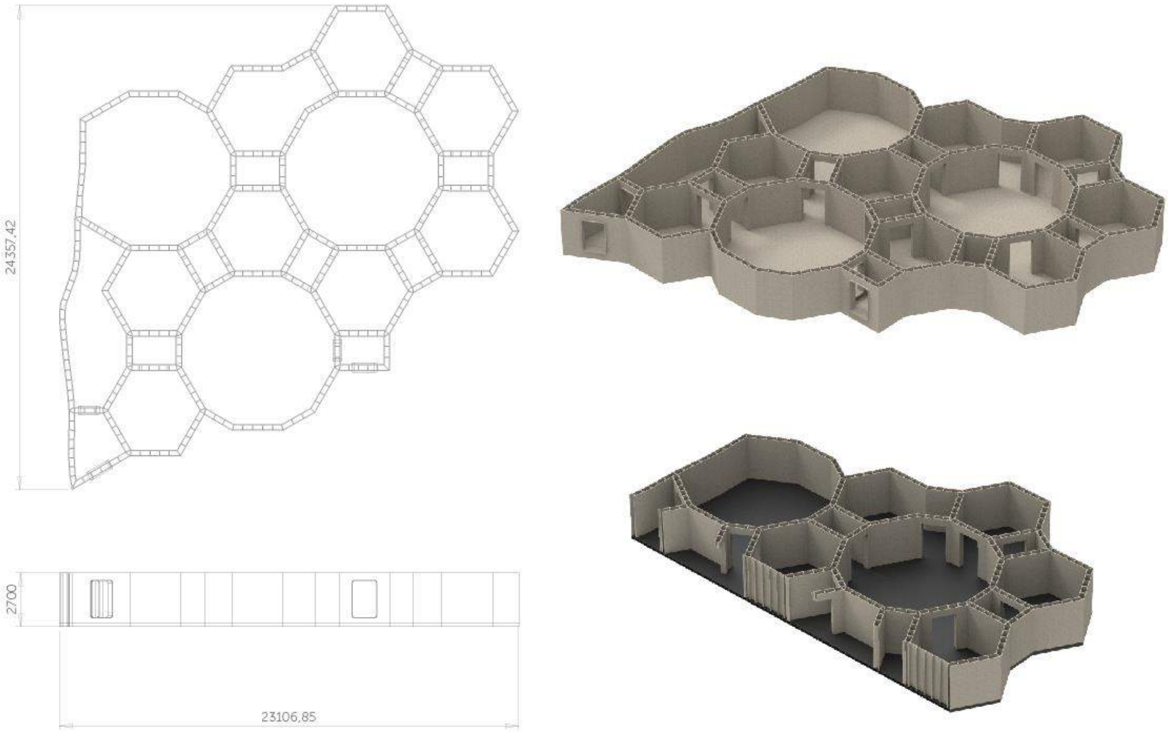

Figure 67 - Technical drawings and modulation of the individual module with section view of the alveolus in the bottom right[15].

Apart from the ground level, the lava tube can also be used in height. Although without much detail, two more levels are proposed in Figure 68 in order to show the maximum use of available space and possible expansion also in a vertical axis.

It is important that the systems which produce oxygen, water and solar power are located within short distance to the habitat, to facilitate maintenance and access. Atmosphere control and supply, air revitalization, temperature and humidity control, water processing, waste management technologies, communication wiring and sewers are integrated in the habitat (floor and ceiling).

To provide optimum living and working conditions, the base will adapt to the environment and the settlers' number and needs, thereby evolving and expanding continuously. A maximum of adaptability in the interior of the colony as well as flexibility in the overall configuration enables the crew to

[15] The black color in the section view was merely used for visual purposes.

configure the space according to their needs and preferences. The proposed design shows how an elementary set of modules could evolve into a settlement and gain increasing self-sufficiency by using local resources.

The colony configuration presented in this chapter is only one of the multiple arrangements that can be done with these modules. It does not exclude the possibility of other configurations nor does it limit the creativity in adapting the modules to the actual lava tubes that will, eventually, be found on Mars. Numerous possibilities can be designed but the main concern should be the maximum possible use of space.

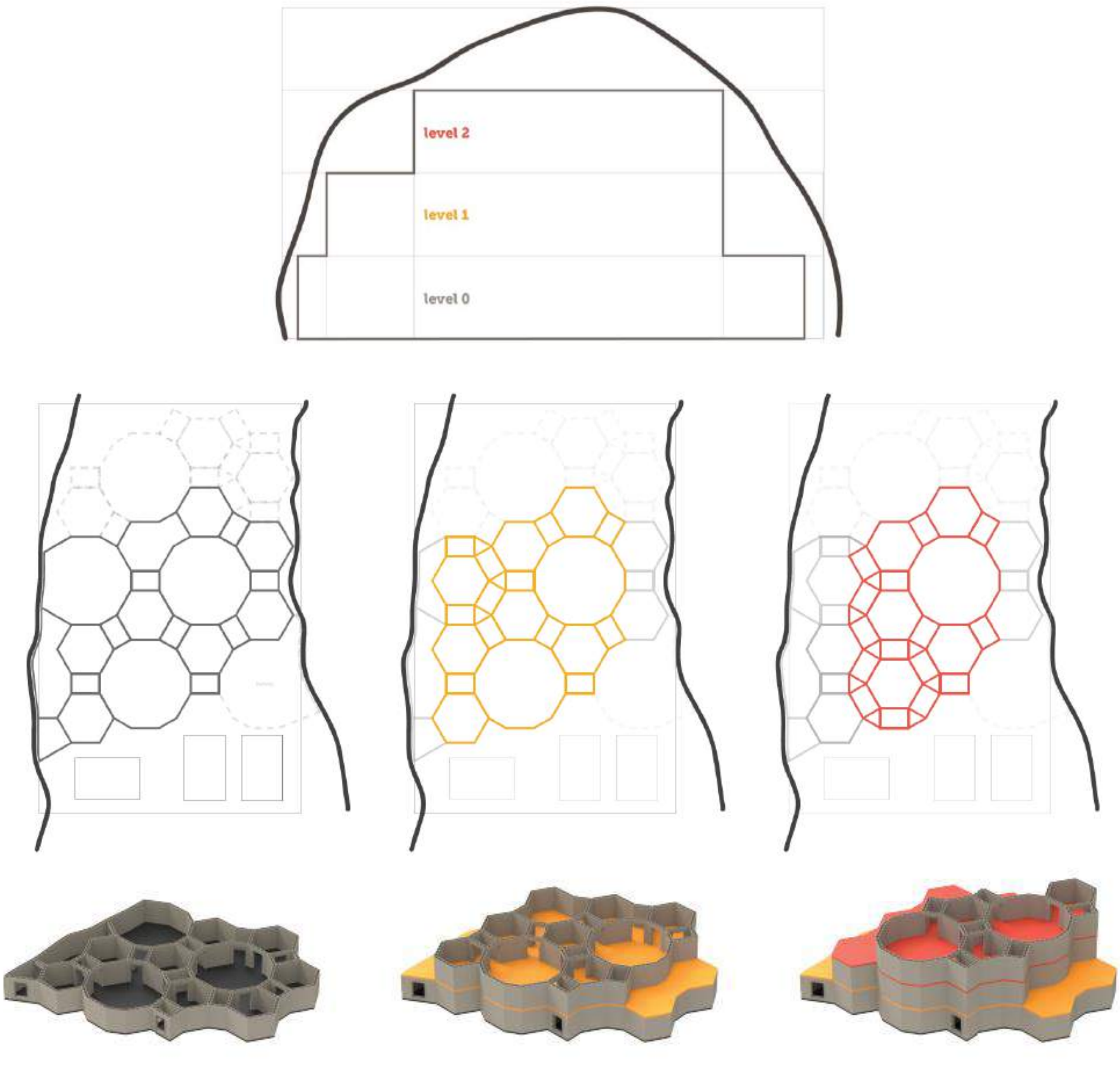

Figure 68 - Left - Ground level; Middle - Middle level; Right - Top level.

Materials

It is not possible nor economically reasonable to rely exclusively on supplies sent from Earth. The logical thing to do is to work with Martian *in-situ* resources and fabricate most of the colony's structures from abundant materials like basalt and regolith as well as manufacture new equipment and replacement parts *on-site*.

The materiality of basalt, 3D printed basalt and basalt textiles need to be explored in the sense of smoothness versus roughness, polished versus natural, cold versus warm, hard versus soft, sharp corners versus round corners, light weight versus heavy, and many other properties. It is important that the finish of basalt is adapted to the object and to the task. The goal is to promote comfort and well-being through the plasticity of the material used. Clean and polished surfaces are a requisite in the kitchen and dining room. This could be achieved by finishing treatments or clean cuts applied to the 3D printed basalt objects. Warm and soft surfaces are crucial for beds, chairs and sofas, which can be solved by the use of basalt fibres intertwined to form a woven fabric. Also, with the addition of electrical resistances basalt stone can be warmed up. In general materials need to be comfortable, durable and light weigh for mobility.

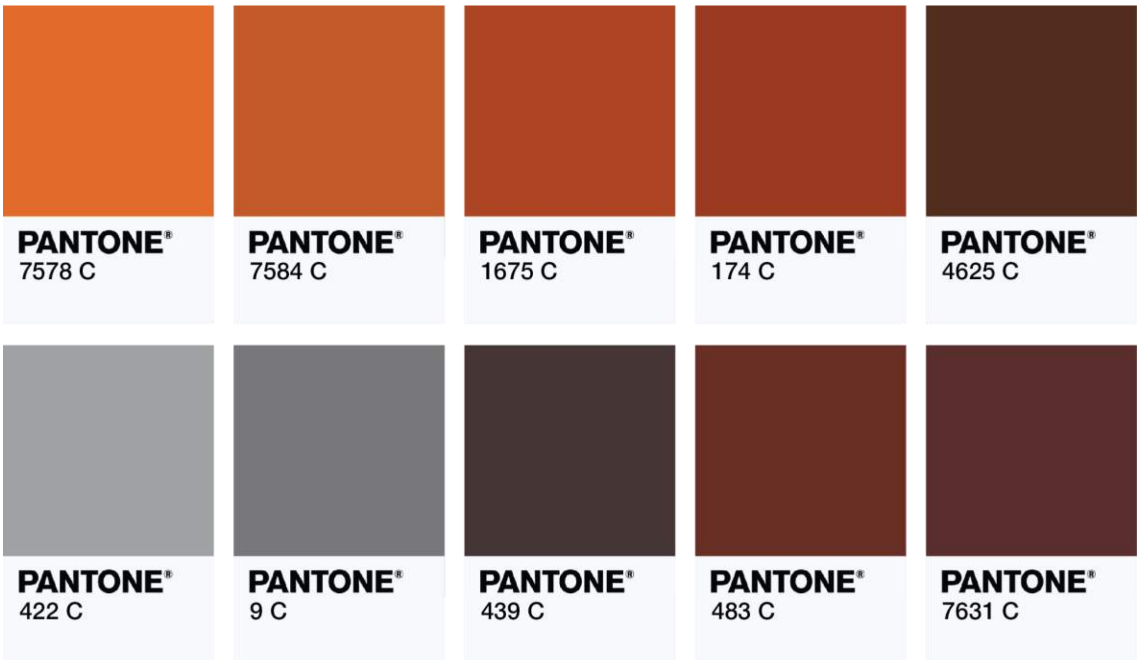

Figure 69 - Mars design pantone by the author.

The colour of the modules' walls and floorings will be as neutral as possible, with basalt's natural colour. Also, the design of the colony and its interior objects should fit the natural environment and the colours of Mars (Figure 69). If necessary, blue and green can be used for contrast. Then, settlers can personalize the space with their own personal preferences of colours, fabrics and other things. In a later stage, the addition of other processed materials such as plastic, wood, metal, among others, is welcome.

Manufacturing process

3D printing technology is an *on-site* manufacturing system that is a pertinent choice for Mars because it is a relatively fast process that does not require the workmanship of specialized people and allows the creation of numerous shapes. The 3D printer robots will extrude the colony's structures with numerical basis (software) an *in-situ* resources, such as basalt and regolith (Figure 70). More structures can be printed anytime and therefore easily expand the habitat.

Using a robotic 3D printer that climbs over the printed structures as they are being printed (see 3D printing, chapter 3), reduces costs and the need for big complex machinery that, for now and on a near future, do not exist on Mars. Also, the use of this robotic 3D printer facilitates the printing on any place on Mars since it can move from one place to another.

The use of 3D printing for structures is also advantageous because the structures can be printed all at once and are ready for use almost immediately after the print is finished. The fact that everything is printed at once is preferable because the joints are to be avoided as they weaken the structure. On Earth we build concrete pillars and then fill the spaces with bricks. This process on Mars is not viable, so printing the entire structures at once with the desired configuration is a more rational approach.

As mentioned in chapter 3, 3D printing with basalt is already being explored by some authors. Of course that this manufacturing technology will require a lot of development before setting foot on Mars but, as they confirm, it can definitely be the prime choice for construction.

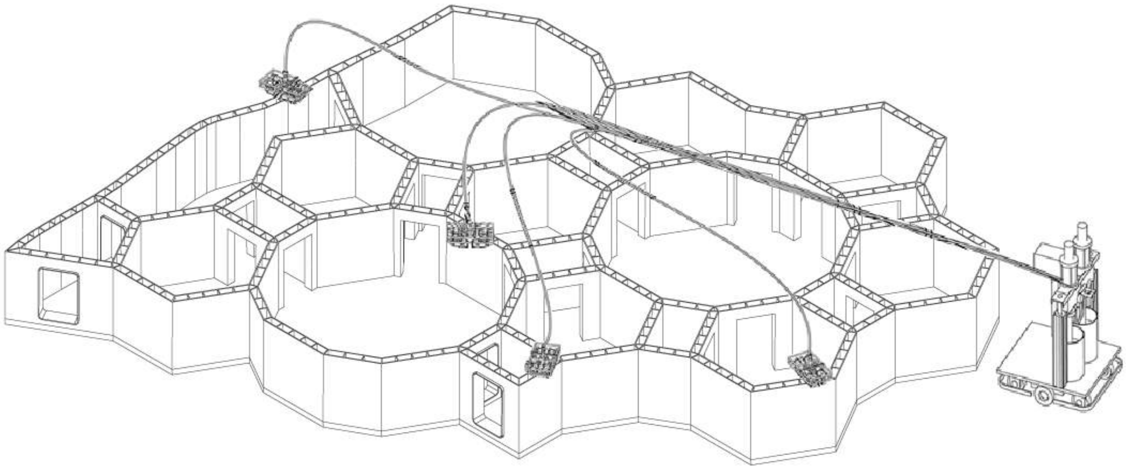

Figure 70 - Simulation of 3D printer climber robots printing the colony. Adapted from "Small robots printing big structures" (Iaac 2018).

Prototypes

In the design process, three-dimensional models are a physical manifestation of a product concept that help the visualization of the proposed ideas. They are tangible and can be picked up, turned over, looked at from different points of view and be assembled and disassembled.

The prototypes of this project were 3D printed in LDPS laboratory at FEUP. The reason why 3D printing was chosen to make the prototype is the fact that the actual colony manufacturing proposal is also 3D printing. However the use of basalt in the 3D printed prototypes was not possible so PLA was used instead.

The individual module prototype (Figure 71) was printed in the *Makerbot Replicator 2X* 3D printer at a 1/50 scale using an orange[16] PLA filament. The final object had to be printed in three parts – walls, floor with alveolus and top of the floor. These parts were not glued together in order to allow the visualization of the disassembled module in more detail. The overall measures are 105mm of length 92mm of width and 54mm of height. Because the *Makerbot Replicator 2X* printer has a minimum print thickness of 0,4mm and prints thicknesses that are multiples of four, the wall thickness of this modulation has been changed to 4cm for visual purposes of the prototype.

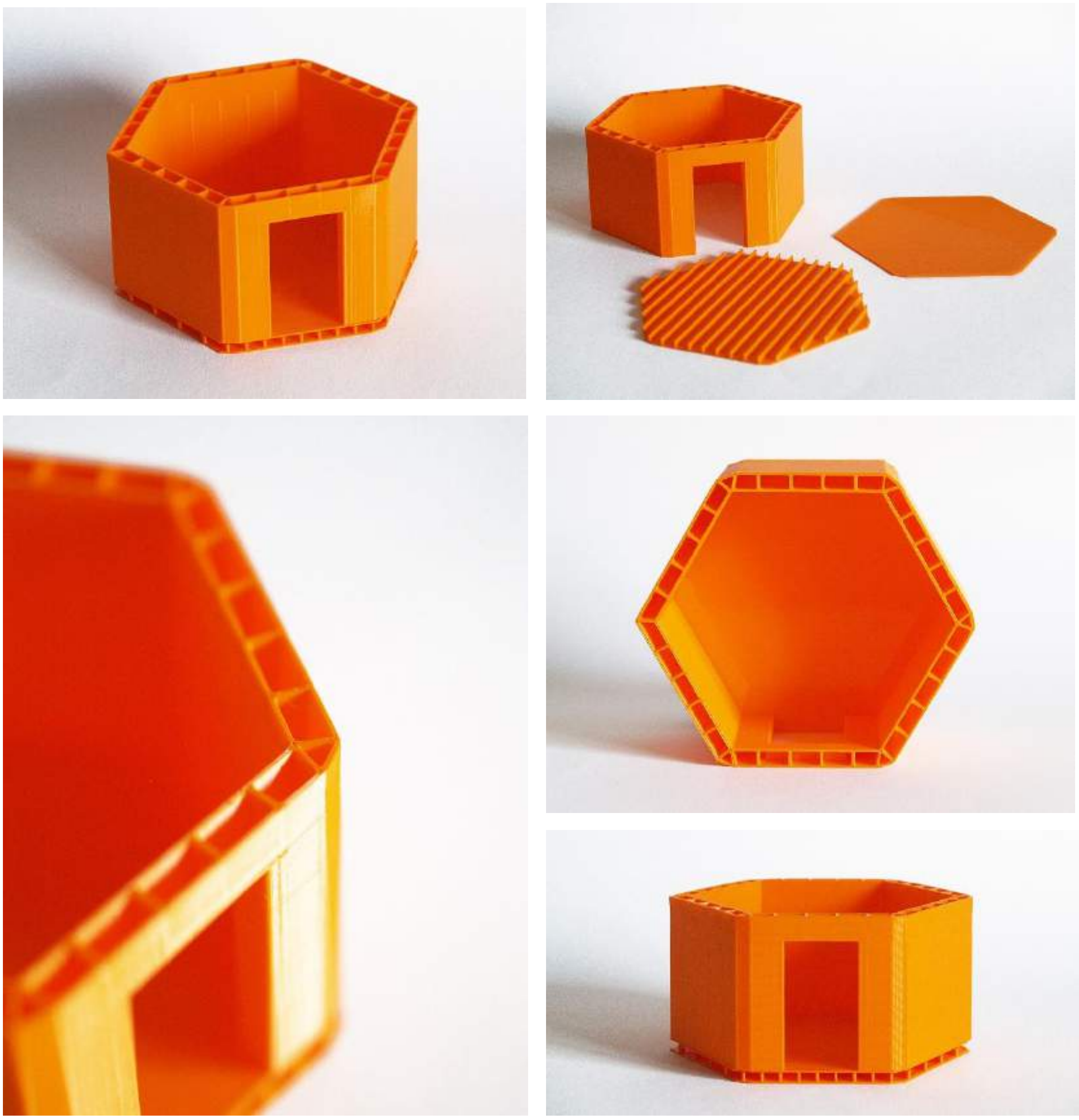

Figure 71 - Individual module's prototype.

[16] The orange color in the module prototype was merely used for visual purposes.

The colony prototype (Figure 72) was also printed in the *Makerbot Replicator 2X* 3D printer but at a 1/100 scale using a grey PLA filament for the walls and a black[17] PLA filament for the floor. The final object had to be printed in four parts - two parts of walls and two parts of floor. All the parts were glued together. The overall measures are 231mm of length 244mm of width and 27mm of height. At 1/100 scale it was not possible to print the alveolus details so the modulation has been changed to completely filled walls for the understanding of the overall shape.

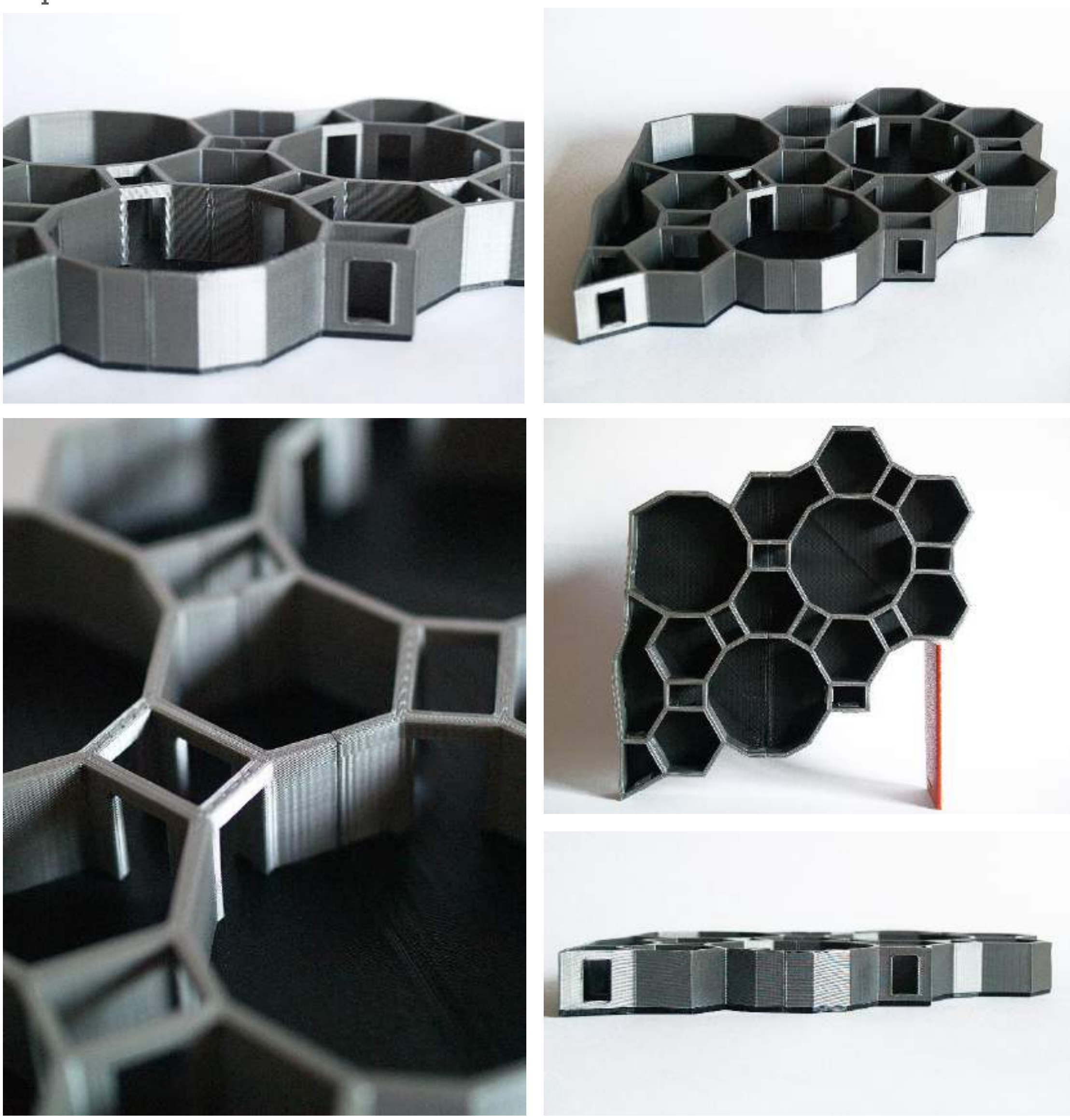

Figure 72 - Colony's prototype.

[17] The grey and black colors in the colony prototype were merely used for visual purposes.

Other design possibilities

The main focus of the design proposal, presented before, was the development of 3D printed structures with basalt. However, other design possibilities were thought throughout the whole process and they interesting to include in this section for a wide scope of future opportunities. As previously explained, the colony proposal is only one example of the numerous possibilities of arrangements of the basic module. The design of this module was the *seed* for a *tree* to grow later, in other words, first it was designed the cell and then many cell arrangements can be done for expansion, creating bigger constructions and even true Martian cities. This module is not exclusively for lava tubes, it can also be built in the surface of the planet.

Regarding the design of the modules, another interesting perspective is the addition of wheels (Figure 73) in order to enable the modules to become mobile. This idea of mobility could be very interesting in the sense that settlers could simply move compartments equipped with the necessary living objects and depart for the exploration of Mars. This would particularly be convenient for scientists, biologists, geologists and other researchers since they would have portable labs. In that way, settlers would "carry their homes on their back" and return to nomadism, *living in motion*[18].

As for flexibility, concepts of furniture on wheels[19], furniture embedded in walls and working with removable, collapsible/expandable[20] (Figure 73), and easy-to-store components would also be very useful in the domestic landscape and provide transformation and economy of space. For that purpose, the use of the basalt fibre textiles[21] could be an interesting option. This fabric could be used to create flexible partitions (Figure 73) that could easily change the room and reconfigure the inside of the colony for maximum adaptability to the settlers' needs and living preferences. It could also be used in the design of everyday objects such as beds, hammocks, sofas, etc.

[18] Mathias Schwartz-Clauss in *Living in Motion* (Schwartz-Clauss and Vegesack 2002).
[19] Ettore Sottsass in *Italy: the new domestic landscape* (Ambasz 1972).
[20] Per Mollerup in *Collapsibles* (Mollerup 2001).
[21] The received basalt fiber textile samples from the Vulkan-Europe B. V. and SwissTulle Ltd.

As mentioned in the materials subchapter, it would be interesting to explore the plasticity of basalt through dichotomies between hard and soft, opaque and transparent, smooth and rough. Surfaces that require some hygiene must be smooth (beds, table covers, chair seats, etc.), but the rest can be perforated (table legs, chair legs, things that are in contact with the floor. That way less material is used and objects become lighter[22].

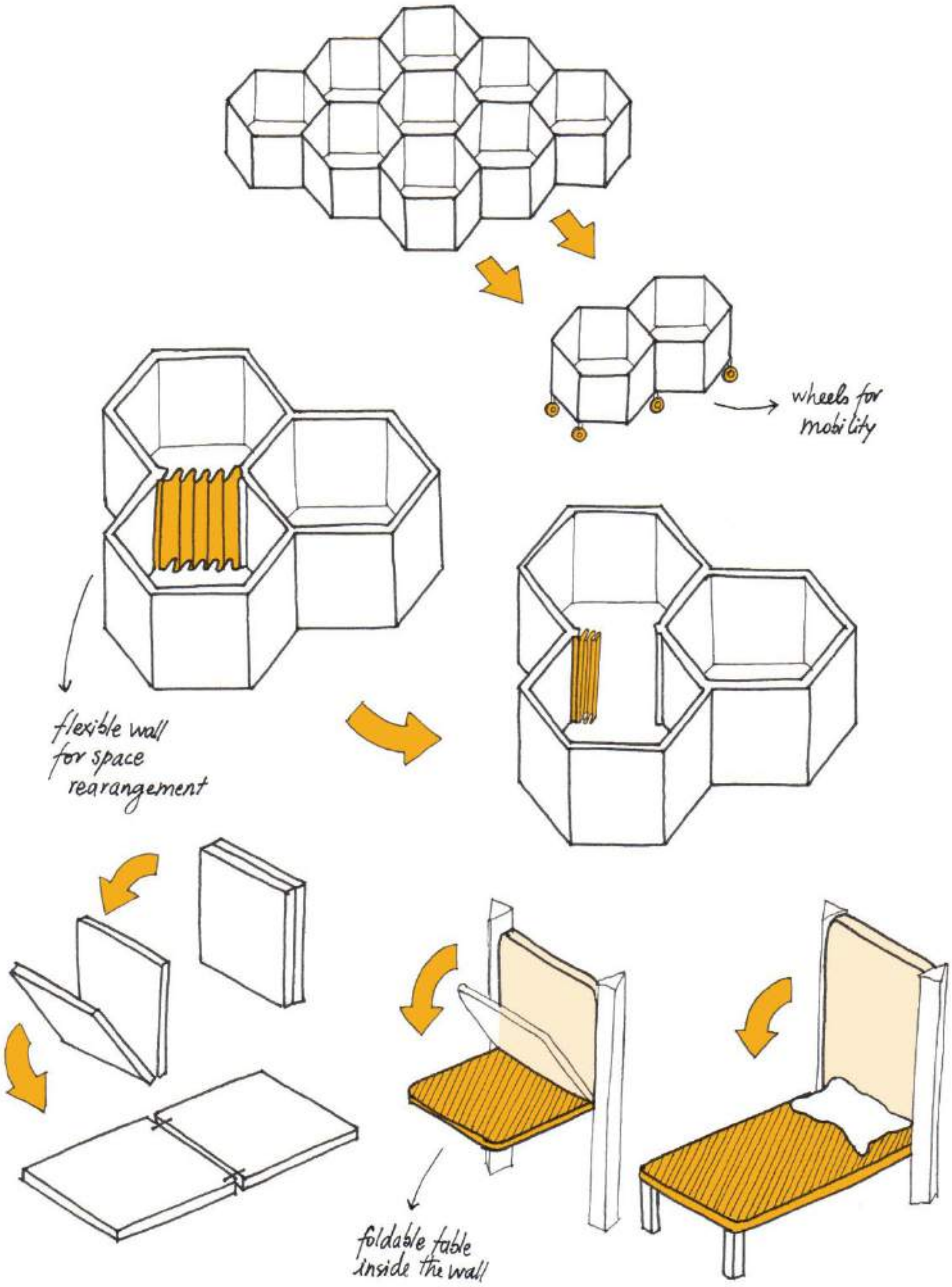

Figure 73 - Sketches of other possible designs.

[22] Adriaan Beukers and Ed van Hinte in *Lightness* (Beukers 1999).

Figure 74 - “Earth --> 225 million kilometres”.

Image retrieved from the movie *The Space Between Us* (Chelsom 2017).

Conclusion

Designing complexity and urgent

The journey of the human being to the planet Mars is becoming less a dream and a deeper and more complex reality. Throughout this investigation it became clear that designing a settlement for Mars represents great potential. However there is still a huge gap in the field of Martian architecture and extra-terrestrial design. Thus, there should be an effort to narrow it and allow multidisciplinary teams of engineers, architects, designers, among others to work together on the design of a user-centred settlement focused on both physical and psychological human requirements.

Designing local, modular and printed

A modular and adaptable approach inspired by nature, allows maximum use of space, minimum use of resources and numerous possibilities of colony configurations with private individual spaces and bigger spaces for families and communal activities. Also, the use of the emerging 3D printing technology simplifies manufacture and further development on this area could result in a true industrial revolution. It is not viable to send materials from Earth to Mars, thus *in-situ* resource utilization must be explored extensively.

Designing material metamorphosis

Transforming a hard basalt stone into a soft fabric is an incredible achievement that lead us to thinking that there is an entire range of opportunities for innovation and creativity awaiting. New ways of living, new ways of interaction between man and machine and new ways of perceiving the environment, will arise on an entirely different landscape.

Designing a future human condition

The development of technologies to reach this goal will also improve the current life on earth, and the same principles can be applied to our mother planet. Colonizing space will not only meet our human condition of discoverers but will also move towards the answer of great questions of humanity and science.

Limitations and future perspectives

The development of this thesis was certainly a long process with its ups and downs like anything in life. Despite that the overall feeling is positive and great enthusiasm for the theme was always a constant.

Compartment arrangements and colony design and measurements were purely experimental. A deeper design study should be performed and the design of a more advanced colony should also be advised by architects and engineers.

The late reception of the basalt fibre fabric samples deprived this work of an entire experimental study on this new amazing material and consequent inclusion in the final design proposal. However, the extended research on this fabric represents a fantastic opportunity and is definitely a future suggestion. It can be applied to numerous things and possibly be used with other materials such as natural resins for hardening. A possible visit to the installations of the contacted companies and others could give a richer perspective on this matter.

Another limitation was the lack of access to basalt 3D printers in order to conduct more realistic material experiments and prototype reliability. Even a ceramics 3D printer would have been closer to the final material, but it also was access limited. Even though the PLA used for the prototypes already gives a close view on the overall shape a recommendation for future development in this area is the use of basalt mixtures for experimentation of 3D printing in order to give a closer feel on the material's plasticity. Obviously, the accuracy and finish of basalt 3D printing objects will also have to be further develop for the future print on planet Mars.

To close this thesis, just like the designer Emilio Ambasz did in the seventies (Ambasz 1972), I too leave an invitation and a call for designers around the world to develop their concept ideas for a *New <u>Red</u> domestic landscape*.

The time to think wide and clear is now.

"Look around and choose your own ground." - *Breathe* in *Dark Side of the Moon* by Pink Floyd

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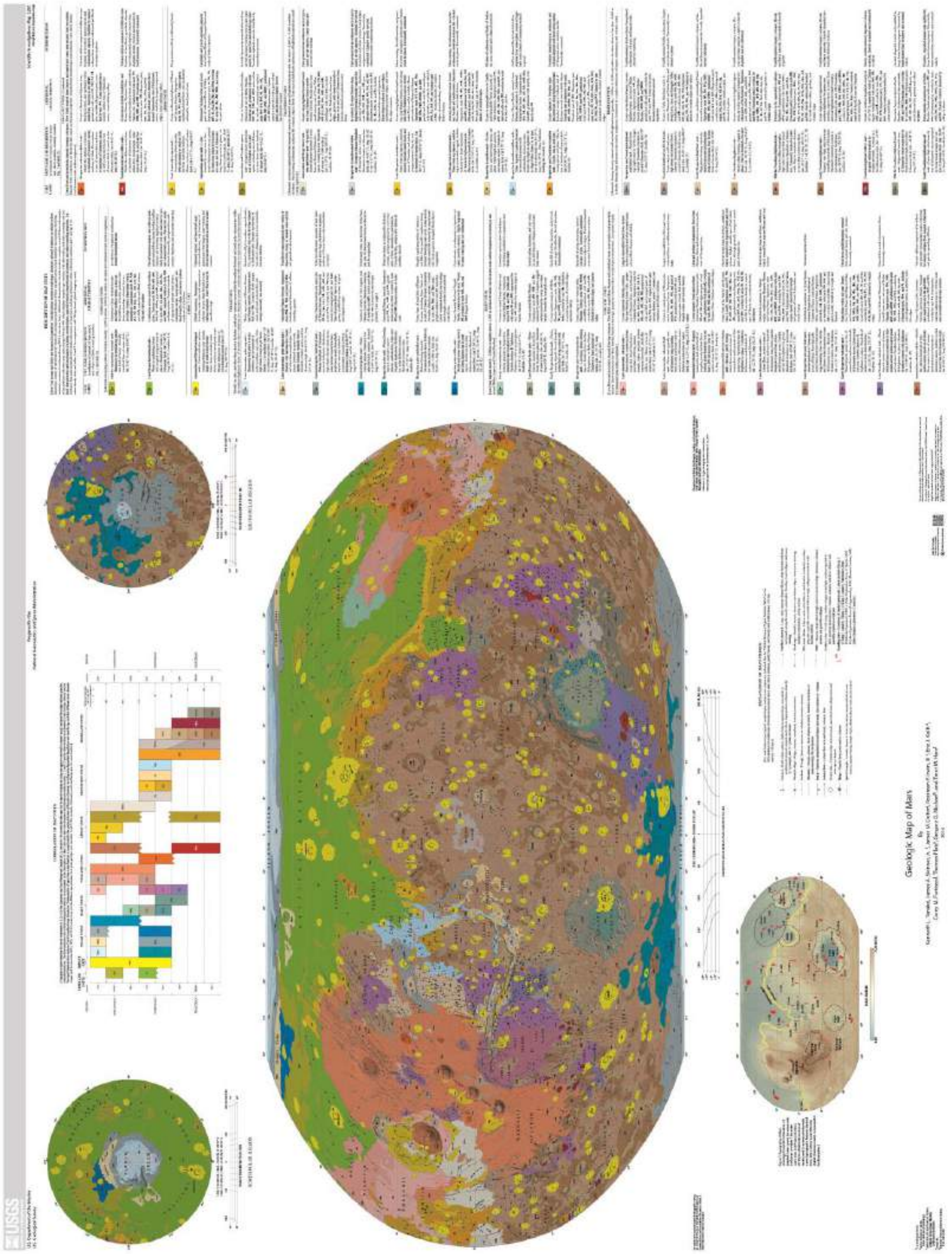
Appendix

Appendix I



Appendix II

Gouda, June 18th, 2018

Hello Filipa Freitas Soares,

Congratulations with your choice - Basalt fibers for dwellings.

With the use of basalt fiber rebars (BFRP) this will never happen!

First about Basalt fiber.

Basalt fiber is a 100% natural product drawn from the lava of melted basalt cobbles (1500 ^{0}C).

By an extrusion method the lava is pushed through very narrow holes - less than a human hair - in that way the basalt fibers are not capable to harden with a crystal structure, but becomes an amorphous structure.

This gives the fibers an exceptional scale of properties.

Such as:

2,5 times stronger than steel, 4 times lighter than steel, no conductivity, no corrosion.

The production of basalt fiber takes only 40% CO_2 in comparison of the production of steel.

The availability is enormous, about 30% of the earth crust is basalt. No deep mines.

Recycling is no problem.

Products:

The fibers are obtained from the melted lava and winded on bobbins. It is called basalt roving.

This is the basic material and from this point of all kind of products are made.

From basalt roving you can make:

Tapes, mats, cords and ropes, nets, etc.

Technical tape obtained by weaving basalt fibers intended for use as load-bearing element, reinforcing elements and pouring concrete to other structures, sealing of static joints of machines and mechanisms, working in a wide range of temperatures and aggressive environments.

For the ease of installation, tape can be manufactured with an adhesive layer on one side.

Basalt Fiber Rebars:

Together with resins - epoxies - you can make rebars and mats: reinforcements for concrete.

Basal Fiber is an effective additive reinforcing additive for foam concrete, polystyrene concrete and just concrete.

Due to its unique physical, chemical and mechanical properties, basalt fiber can be used in conditions, where other materials do not work or require periodic replacement or maintenance.

The scope of application of basalt fiber:

- Construction of civil engineering objects. Building structures of concrete, particularly effective for use in regions of high seismic instability and man-made structures undergrounds
- Concrete floor screeds and industrial floors.
- Sea bars and facilities and other areas of use of concrete, where constant erosion leads to surface abrasion.
- Hydraulics structures such as reservoirs, sewage tanks, weirs, ports, docks and marine barriers.
- Concrete roads and bridges, asphalt, especially important where high resistance to penetration of salts is required.
- Construction of bridges, runways of airfields, waterworks (embankments and dams, locks and channels of rivers).
- Strengthening and repair of domes of mines and tunnels.
- Creation of different types of road surfaces precast and monolithic plates, dividing strips.
- Production of paving slabs, curbs and gutters.
- Production of small architectural forms and decorative elements, etc.

Properties of basalt fiber:

- Significantly increases the impact and fatigue strength.
- Significantly increases the tensile strength and tear.
- Increases resistance to mechanical stress, significantly reduces shrinkage deformation.
- Provides three-dimensional reinforcement material.
- Increases resistance to abrasion.
- Increases crack resistance, ensures the absence of shrinkage cracks and stress cracks.
- Eliminates the appearance of plastic deformation, flaking the surface.
- Has high adhesion to the solution and forms homogeneous mass.
- Increases frost resistance and water resistance.
- Has absolute incombustibility, gives resistance and fire resistance material (working temperatures range from - 260 ^{0}C up to 750 ^{0}C).
- Structural strength in the entire temperature range.
- Environmentally and chemically pure (basalt fiber = 100% stone) and durable material.
- Resistance to aggressive environments.
- Gives the uniformity of porous structure.

Specifications of basalt fiber.

The cut lenght of chopped fiber in mm: (3, 6, 12, 18, 24,…70) ± 1.5mm The length of the fiber can be made of a multiple of 3. See picture below.

The diameter of elementary fiber, microns: 12 ± 1.5

Humidity, %, not more: 0.3

The modulus of elasticity, GPA: minimum 75.

Coefficient of thermal conductivity W/MK: 0.031 inch - 0.038

Chemical resistance, weight loss after 3 hours boiling. H_2O - 2%, 2N Paon – 3%, 2N HCI - 2.2%

Basalt Fiber products for dwellings.

Chopped fiber for the use in a concrete mix

The term BFRP is often used instead of saying Basalt Rebar.

BFRP reinforcement in concrete constructions.

Basalt Fiber Profiles as a construction profile.

VULKAN Europe BV. Continuous Basalt Fiber Distribution

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Mob: +31 6 54 907 214

E-mail : j.dewit@vulkan-europe.com

Web site : www.vulkan-europe.com

Appendix III

VULKAN Continuous Basalt Fiber Distribution
Europe BV

Filipa Freitas Soares
Rua 20de Julho no 18 , 1° esq
Vila Real
Portugal 5000-442

Gouda, 19-7-2018

Hello Filipa Soares ,

Sorry you had to wait so long , but I ran more or less out of samples .

So now you will receive my last sample .

I think I have given you all the specifics of basalt fiber already.

The fabric you receive is 100% basalt.
So can consider it as a product of nature.

The basalt stone cobbles are melted in a furnace with a temperature of 1500 C° which brings is up to lava.
This lava is pushed by pultrusion technics through very tiny holes , thinner than a human hair and it becomes this basalt fiber.

The difference between basalt stone and basalt stone fiber is that by this pultrusion technic the basalt is not able to crystalize in it nature form but it becomes an amorphous structure instead of a crystaline structure.

Please be aware that no other ingredients were applied to the lava.
So it is still 100% basalt.

1

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Chamber of Com. 54673097

VULKAN Continuous Basalt Fiber Distribution
Europe BV

So the main properties of basalt stone are still kept and gives the fiber is extraordinary properties , such as 2,5 stronger than steel, 4 times lighter than steel , no conductivity , no corrosion , these properties remain till a temperature of + 800 C° and -200 C°

Basalt fiber can be considered as a new commodity , although its origin is already billions of years old.

I also give you an example of cord made with basalt fiber.

In my profession as a building engineer we use basalt fiber rebars now in the concrete beams and floors as an alternative for steel reinforcement in the concrete.

Please also look at my web-site for more information.

About 3D-printing in most cases the basalt fiber is used to reinforce the mother material which is printed and because of its nature it does not influence this mother material.
A friend of mine uses is in the medical sector for artificial bones.

I will be very happy to receive a copy of your thesis .

Good luck

Hans de Wit

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Appendix IV

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Filipa Soares
Rua 20 de Julho
n° 18, 1° esq.
PRT–5000 – 442 Vila Real

CH-9542 Münchwilen, 14 August 2018

Basalt samples

Dear Filipa

Thank you for your interest in our basalt qualities. We are pleased to send you enclosed the following samples as well as the technical specifications:

- **2.05427**
- **2.05309**
- **2.02781**

Should you need any further information please do not hesitate to contact us.

Yours sincerely

swisstulle Ltd.

Gülsüm Görgülü
Head of Customer Service

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F-Artikelspezifikation

Kundendaten:

Name: ME-Projekt 5155
I/Artikel Nr.:
I/Auftrags Nr.:

Herstellerdaten:

Name: swisstulle AG
Artikel Nr.: 2.05427
U/Auftrags Nr.: VM 01924
Stück Nr.:
Lieferschein Nr.:
Lieferung vom:

Produktdaten:

Verwendungszweck: Technisches Gewirk
Material: 100%Basalt
Ausrüstung: -
Farbe: rohfarbig
Breite: 240cm

Tests:

Merkmal *Description*	**Norm** *Standard*	**Einheit** *Measures*	**Sollwert** *Calculated data*	**Toleranz** *Tolerance*	**Istwert** *Actual data*
Flächengewicht *Weight*	DIN EN 12127	g/m²			292
Dicke *Thickness*	EN ISO 5084	mm			0.83
Höchstzugkraft *Tensile strength* Kette/*lengthwise* Schuss/*across*	EN ISO 13934-1	N/5cm			 46 49
Höchstzugkraft-Dehnung *Tensile elongation* Kette/*lengthwise* Schuss/*across*	EN ISO 13934-1	%			 18 52
Berstdruck *Burst strength*	DIN EN ISO 13938-2	kPa			160
Massänderung nach Wärmeeinwirkung *Dimension stability 100°C, 24h* Kette/*lenghtwise* Schuss/*across*	DIN 53377	%			 -0.2 -1.0

Entwicklung/
Person in charge for tests: **Datum/Visum 19.06.2013/** P. [signature]

Technik/
Person in charge for technique: **Datum/Visum 19.06.2013/** [signature]


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2.05427
Article 2.05427
Material 100 % Basalt
Colour rohfarbig
Weight 292 gr/m2
Width 300 cm

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F-Artikelspezifikation

Kundendaten:

Name: ME-Projekt 5067
I/Artikel Nr.:
I/Auftrags Nr.:

Herstellerdaten:

Name: swisstulle AG
Artikel Nr.: 2.05309
U/Auftrags Nr.:
Stück Nr.:
Lieferschein Nr.:
Lieferung vom:

Produktdaten:

Verwendungszweck: Technisches Gewirk
Material: 94%Basalt / 6%PES
Breite: 300cm
Ausrüstung: -
Farbe: rohfarbig

Tests:

Merkmal *Description*	**Norm** *Standard*	**Einheit** *Measures*	**Sollwert** *Calculated data*	**Toleranz** *Tolerance*	**Istwert** *Actual data*
Flächengewicht *Weight*	DIN EN 12127	g/m²			299
Dicke *Thickness*	EN ISO 5084	mm			1.29
Höchstzugkraft *Tensile strength* Kette/*lengthwise* Schuss/*across*	EN ISO 13934-1	N/5cm			 602 328
Höchstzugkraft-Dehnung *Tensile elongation* Kette/*lengthwise* Schuss/*across*	EN ISO 13934-1	%			 15 48

Entwicklung/
Person in charge for tests: **Datum/Visum 25.06.2013/**

Technik/
Person in charge for technique: **Datum/Visum 25.06.2013/**

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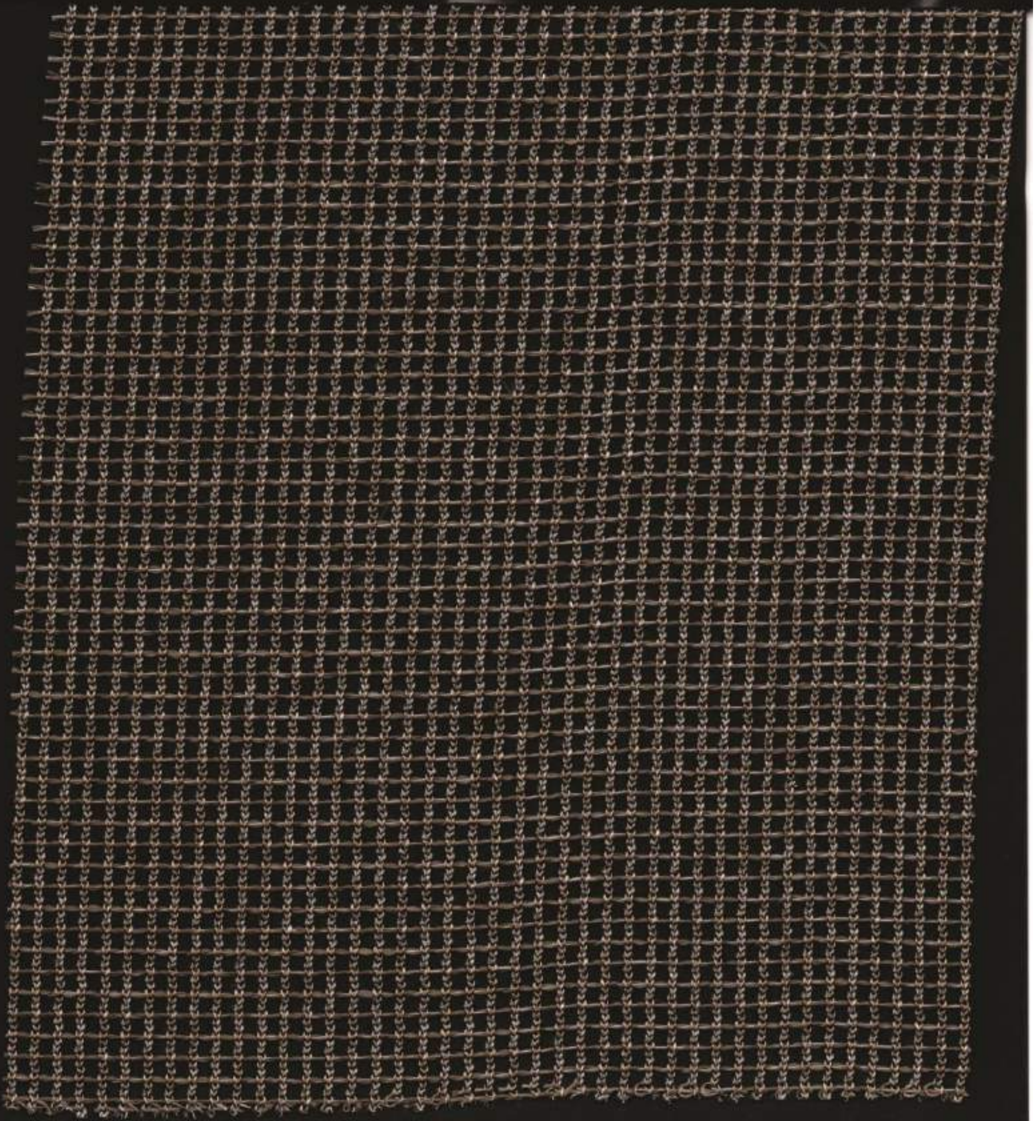

2.05309

Article	2.05309
Material	94% Basalt 6%PES
Colour	Rohfarbig
Weight	229gr/m2
Width	300 cm
Finish	-

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F-Artikelspezifikation

Kundendaten:

Name: Projekt 2144
I/Artikel Nr.:
I/Auftrags Nr.:

Herstellerdaten:

Name: swisstulle AG
Artikel Nr.: 2.02781
U/Auftrags Nr.: VM 01674
Stück Nr.:
Lieferschein Nr.:
Lieferung vom:

Produktdaten:

Verwendungszweck: Technisches Gewirk
Material: 100% Basalt
Ausrüstung: S+
Farbe: rohfarbig
Breite: 370cm +/-1%

Tests:

Merkmal *Description*	**Norm** *Standard*	**Einheit** *Measures*	**Sollwert** *Calculated data*	**Toleranz** *Tolerance*	**Istwert** *Actual data*
Flächengewicht *Weight*	DIN EN 12127	g/m²			250
Dicke *Thickness*	EN ISO 5084	mm			1.95
Bemerkung: -					

Entwicklung/
Person in charge for tests: **Datum/Visum 02.11.2011/**

Technik/
Person in charge for technique: **Datum/Visum 02.11.2011/**

2.02781_01FD_FE
Original auf dem Netz

Verantwortung: rf
Seite 1 von 1

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2.02781

Article	2.02781 Proj.2144
Material	94 % Basalt / 6 % Solvron (PVA)
Colour	raw fixed
Holes	-
Weight	250 gr/m2
Width	370 cm
Finish	-